HIGHWAY RESEARCH REPORT

SHALLOW SEISMIC TECHNIQUES

FINAL REPORT

STATE OF CALIFORNIA

BUSINESS AND TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMEN

RESEARCH REPORT

CA-HY-MR-2951-1-73-18

Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration June, 1973

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Shallow Seismic Techniques		5. REPORT DATE June 1973 6. PERFORMING ORGANIZATION CODE 19203-762503-632951
7. AUTHOR(S) Stephens, Elgar E.		8. PERFORMING ORGANIZATION REPORT NO. CA-HY-MR-2951-1-73-18
9. PERFORMING ORGANIZATION NAME AND ADDRESS Materials and Research Department California Division of Highways Sacramento, California 95819		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. F-7-88
12. SPONSORING AGENCY NAME AND ADDRESS California Division of Highways Sacramento, California 95807		13. TYPE OF REPORT & PERIOD COVERED Final 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This was a three phase field investigation of shallow seismic techniques to determine their application to highway problems. Phase 1 was an evaluation of wave sources, wave detectors and seismic instruments. Phase 2 was a study of refracted compressional waves, reflected waves, uphole waves, surface waves and shear waves. Phase 3 was an evaluation of the accuracy of predictions based on seismic information.

Two wave sources were studied, hammer blows and explosives. The best wave from a hammer blow was provided by the heaviest hammer tested (16 lb.) striking an aluminum plate. Shear waves were generated by horizontal hammer blows against an aluminum bar held in place by one wheel of the vehicle.

Different types of explosives were tested in boreholes and on the ground surface. Buried charges of ammonium nitrate and fuel oil provided the best wave source for investigating low velocity material.

Several different wave detectors were studied. The 8 hertz phones weighing about 5 ounces were best for routine refraction work. For special purposes such as reflection or shear wave recording, the 8 hertz geophone arrays performed best.

(continued)

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Seismic, wave sources, geophones, instruments, refraction, reflection, shear waves, uphole velocities, surface waves.	Unlimited

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	78	

HMRT - 1242 (ORIG. 9/72)

TECHNICAL REPORT STANDARD TITLE PAGE

16. Abstract (continued)

Seismic instruments tested were the Electro-tech ER-75-12, Bison Models A and B, and the Huntec FS-3. All are suitable for routine seismic investigations, but differ in their suitability for specific applications.

A study of refracted and uphole velocities indicated the refracted velocities gave a better indication of the physical properties of a material. Shear waves were collected and used to determine dynamic moduli of the materials. Reflections could not be obtained at most of the test sites because of interference from shallow refractions.

STATE OF CALIFORNIA—TRANSPORTATION AGENCY RONALD REAGAN, Governor

DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
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June 1973
Final Report
M&R 632951
F-7-88

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a research report titled:

SHALLOW SEISMIC TECHNIQUES

Marvin L. McCauley
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Very truly yours,

JOHN L. BEATON
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ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Robert and William Lawson, owners of the Diamond Springs Lime Company; and to the mine superintendent, Leonard Bartley, for their generosity in allowing the use of their mine and equipment for a part of this study.

Special thanks are extended to Tom Hoover, Ralph Fitzpatrick and Paul Salinas for their efforts in assisting with the field work.

This investigation was made in cooperation with the U. S. Department of Transportation, Federal Highway Administration, (Federal Program No. HPR-PR 1(7), F-7-88).

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INTRODUCTION

Since 1951 the California Division of Highways has made extensive use of refracted compressional waves to aid in the design of cut slopes and prediction of excavation characteristics. This method is fast, reliable and inexpensive. Considerable success has been experienced with its use; however, for certain materials and subsurface structures the compressional wave velocity does not correlate directly with such characteristics as strength or hardness.

Most of our work is within 100 feet of the surface, although occasionally depths of 200 or 300 feet are required. It was therefore decided to study recent developments in shallow seismic techniques to determine their application to highway problems. There were several techniques which appeared to have applications in highway work. The seismic reflection method seemed to have applications in uphole studies and in detecting soft layers beneath hard layers. Shear waves appeared to be useful in determining excavation characteristics, groundwater tables and the dynamic moduli of the materials. Studies using the different techniques had not been comprehensive or practical enough to evaluate potential application of these techniques to highway work.

The work on this project consisted of three phases. Phase 1 was a field evaluation of wave sources, wave detectors and seismic instruments. Phase 2 was a study of refracted compressional waves, reflected waves, uphole waves, surface waves and shear waves to determine possible applications to highway problems. There was reason to believe major benefits could be derived from the application of shear waves and consequently a major part of the investigation was devoted to their study. Phase 3 was a field evaluation made during or after construction to determine the accuracy of predictions based on seismic data from each area.

The orderly progression of the three phases was disrupted early in the study when a stisfactory source for generating shear waves could not be found. As a result of the time spent on this portion of the study all of the Phase 3 evaluations were not completed.

CONCLUSIONS AND RECOMMENDATIONS

The Conclusions and Recommendations Sections are being presented together because of the several highly specialized areas of investigations and recommendations resulting thereof. Each major research conclusion is followed by a recommendation for implementation of that finding.

Wave Sources

Conclusion: The 16 pound hammer generated a stronger seismic wave than any other hammer investigated.

Recommendation: The hammer used for generating seismic waves should be the largest one the hammer man can comfortably swing, with a weight of at least ten pounds.

Conclusion: More energy was transmitted to the geophone by an aluminum than by a steel strike plate. Also, a small plate transmitted more energy than a larger one, provided the plate was large enough to resist being driven into the soil.

Recommendation: An aluminum strike plate should be used as the coupler. On surveys over material of varying hardness, two plates should be used; one about 6 x 6 x 1 inches and the other with about twice that amount of surface area.

Conclusion: A low velocity explosive such as ammonium nitrate and fuel oil transferred more energy to the soil than did the high velocity explosives.

Recommendation: Seismic lines that require large amounts of energy should be shot with a low velocity explosive as the wave source.

Conclusion: It was more difficult to generate shear waves than compressional waves, and was not possible to generate shear waves at every location.

Recommendation: Additional studies should be made to determine the possibility of using a vibrating energy source instead of an impact to generate shear waves.

Wave Detectors

Conclusion: The 8 hertz geophone was best of those tested for recording a relatively sharp, high amplitude break.

Recommendation: The 8 hertz geophones should be used for routine refraction work.

Conclusion: Horizontal geophones were more affected by wind noise than were the vertical phones.

Recommendation: The horizontal geophones should be equipped with round planting spikes which would allow them to be better coupled to the soil.

Conclusion: Different geophones with the same nominal specifications may respond differently to a given excitation.

Recommendation: Matched pairs of geophones with identical response should be used with the Huntec instrument in order to make full use of that instruments correlator circuit.

Instruments

Conclusion: The Electro-tech and Bison are effective instruments for routine seismic surveys. The Huntec is less desirable for routine work, but is more desirable for collecting shear waves and for doing hammer reflection work.

Recommendation: The Electro-tech should continue to be used as our primary instrument for investigating deep cuts or materials where there is difficulty in transmitting energy from the source to the geophone. The energy source for this type work should be provided by explosives.

The Bison, particularly the model B, should be used at locations where the use of explosives is not possible or is inconvenient, and on those projects where the sledge hammer provides adequate energy.

The Huntec should be used for recording shear waves and for use where two receiving channels are needed, such as for hammer reflection work.

Conclusion: The geophone cable can act as an antenna, receiving a signal and conducting it to the instrument in those areas where stray electromagnetic energy is present.

Recommendation: A shielded geophone cable should be used in areas of high electromagnetic noise.

Seismic Techniques

Conclusion: The seismic velocities from different wave sources were the same for distances up to 600 feet, provided the energy level was sufficient for the instrument to record first arrivals.

Recommendation: When recording seismic waves from a hammer blow, the amplifier gain should be sufficient to record considerable noise to insure recording of the first arrival. Readings should be repeated to verify that reading is a true arrival time and not random noise.

Conclusion: Uphole velocities do not always correlate with other seismic velocities. Predictions of excavation characteristics based on uphole velocities are less likely to be correct than such predictions based on other seismic data.

Recommendation: The practice of obtaining uphole velocities should be discontinued. An alternative, at locations where refraction lines can not be used, would be crosshole velocities.

Conclusion: The hammer reflection method can be used successfully only when subsurface conditions are favorable. Most of the conditions encountered in engineering investigations are not favorable to this method.

Recommendation: The use of the hammer reflection method should be limited to those cases where there is a relatively deep layer of homogeneous material at the surface.

Conclusion: The graph of the dynamic modulus of elasticity versus the compressional velocity indicates an apparent correlation.

TESTING

A large number of tests were conducted during this study at many different sites throughout the state, and included a variety of geologic materials. Methods tested included different wave sources, wave detectors, seismic instruments, and various seismic techniques. Each test is described in detail under a separate heading listing the item or technique involved.

New types of equipment or techniques that were demonatrated to be better than the existing item or method were immediately incorporated into our regular seismic investigations.

WAVE SOURCES

Compressional, Hammer

The first part of this investigation was to determine the best method for generating seismic waves. The seismic waves were from two sources - sledge hammer blows and explosions, and were for the purpose of generating either shear or compressional waves. This part of the report covers the generation of compressional waves from hammer blows.

The generation of a seismic wave from a hammer blow involves two pieces of equipment - the hammer and a coupler for transferring the energy from the hammer into the ground. Both pieces of equipment require evaluation in the test method. A review of commercially available products revealed that hammers provided with seismic instruments usually weigh between 8 and 12 pounds and that couplers are available in a variety of shapes, sizes and compositions.

Previous experience with a four-inch steel ball had indicated it was a good coupler in loose gravel, though a difficult target to hit squarely. On soft ground the ball would be completely embedded by one solid blow. The weight of the four inch ball was 9.5 pounds, and any increase in the diameter would have made the ball too heavy to be easily portable. It is our belief that a hammer seismograph should be completely portable. For these reasons, steel balls were not considered in the tests. The couplers that were tested were flat plates small enough to be considered portable. It was considered necessary for these plates to withstand many repeat blows and still be effective as couplers. Previous experience with steel plates had indicated that plates of less than one-half inch thickness tended to deform from repeated hammer blows. Experience had suggested that when the plates deformed they became less effective as couplers.

With these restrictions, two steel plates were chosen to be tested. One was 4 x 4 x 3/4 inches and one was 8 x 12 x 3/4 inches. The larger one was considered too heavy for field use; but was tested in order to compare the relative advantages of the two sizes.

The strike plates and hammers were tested simultaneously. The test was performed using hammers that weighed 8, 10, 12 and 16 pounds, and two different men to swing them. The amount of energy delivered to the plate by each blow was calculated by measuring the velocity of the hammer just before impact. The amplitude of the geophone breaks was measured to determine the amount of energy arriving at geophones placed at 30, 45 and 150 feet from the strike plate.

The calculated amount of energy delivered to the strike plate by the hammer did not correlate with the amplitude of the geophone signal. This method of determining effectiveness of the coupler was then abandoned. There was good correlation between amplitude of geophone break and hammer size, hammer swinger and plate size. In all cases, a heavier hammer gave a higher amplitude break than a lighter one used by the same person to hit the same strike plate. The bigger man did better with all hammers than his smaller counterpart. And, finally, both men achieved better results with each of the four hammers when striking the smaller plate.

The better performance of the smaller plate may have been a function of the ground condition. At this particular site, the ground was dry and hard, so the plates did not become embedded in the ground. The plates did tend to bounce and ring with a high frequency sound if not struck squarely. When this happened, the amplitude of the geophone break was less than from solid blows that did not result in the plate bouncing.

An aluminum strike plate measuring 6 x 6 x 1 inches was added to the two steel plates for the next test. In addition, one set of records was collected by impacting directly on the ground without using a strike plate.

The results of the second test were measured by the amplitude of geophones at distances of 30, 45, 70 and 95 feet. The largest hammer gave the best results when used by either man on any strike plate. The bigger man also did better than the smaller on any strike plate. The best plate was the 6 x 6 x 1 inch aluminum. There was a noticeably lower frequency sound of the blow and a lessened amount of bounce of the aluminum plate as compared to the steel plates. Behind the aluminum plate, in decreasing order of effectiveness came the 4 x 4 inch steel plate, 8 x 12 inch steel plate, and the direct blow to the ground. Impacting directly on the ground caused plastic deformation and rupture of the ground surface and apparently resulted in poor transmission of energy.

The next test of strike plates and hammers was on moist, soft to firm soil. The plates used were the 4 x 4 inch steel 8 x 12 inch steel, 6 x 6 inch aluminum and 7 x 12 inch aluminum. The 8, 10, 12 and 16 pound hammers were again used. The results were again measured by amplitude of geophone break. The 16 pound hammer again delivered the most energy to the geophone. On this material, the 7 x 12 aluminum plate transmitted the most energy, with the 6 x 6 aluminum plate transmitting less and the two steel plates transmitting the least amount. The

7 x 12 aluminum plate was only 3/4 inch thick and by the end of the test had begun to deform. When plate deformation occurred, a lesser amount of energy reached the geophones.

Other tests at several different locations have confirmed the aluminum strike plates to be better couplers than steel plates. The aluminum plate is also more desirable for field use because of the significant weight difference.

A plastic deformation of the plate by bending or of the soil by the plate being driven into it results in local dissipation of the energy and less is transmitted to the geophone. The size of the plate to be used is determined by surface soil conditions. The smaller plate is better when it can be used, but, the plate must be large enough to resist being driven into the ground. Because of the light weight of aluminum, two different size strike plates can be carried to the field. This makes it possible to get best results when changing soil conditions require different size plates.

Other attempts were made to determine the effect of not using a strike plate on hard material. The first test was on asphalt pavement, laid over a cement treated base. A small amount of deformation occurred at the point of impact, and less energy was transmitted to the geophone than when a plate was used.

An attempt was also made to record on limestone without using a strike plate. A small amount of crushing of the rock occurred at the point of hammer impact. Less damage was done to the rock and a better transfer of energy took place when the face of the hammer was parallel to the rock at the moment of impact. However, the rock was not smooth enough to always be parallel. Consequently, the effects of the hammer blows were not completely reproducible. One or two blows to the plate usually crushed any small highs, allowing the plate to be seated. Subsequent blows than generated reproducible signals.

When this test was repeated on solid quartz diorite, the results were inconclusive. No apparent deformation occurred at the point of impact but results seemed to be more consistent when using a strike plate.

No tests were performed using in-place cobbles or boulders as strike plates. The tests that were performed indicated the size and composition of a strike plate affected the amount of energy transmitted to a geophone. The tests also indicated that impacting the ground directly gave results that were less reproducible and delivered less energy to the geophone than impacting a strike plate. The researcher therefore concluded, that using any object other than a strike plate would affect record quality by introducing an unknown variable into each recorded arrival time.

Shear

The determination of a satisfactory means of generating shear waves from a hammer blow was investigated using different objects as couplers. Most of them were not satisfactory, and did not generate enough shear energy to allow the study to proceed. All early shear wave couplers were of steel, as had been the early compressional wave plates. It was only after the use of steel had been discontinued that any real progress was made.

The first coupler tried was of heavy steel plate shaped much like a kitchen chair. In use, the legs were driven into the ground and the back impacted with the hammer. Another early coupler tried was a steel highway sign post with a flat plate welded to it. The post was driven into the ground to a depth of about three feet and the flat plate was impacted with the hammer. An L shaped piece of steel plate was used by placing it against the side of a trench or against the side of an in place rock. This device could not be held firmly in place, and when loose would generate more compressional waves than shear waves. Attempts were then made to use the large in place rocks by impacting them directly without using a strike plate. The next coupler tried was a round steel bar, 1-1/2 inches in diameter by 4 feet long. A steel collar, just large enough to fit over the bar and about four inches long by 3 inches in diameter was used to increase the size of the target area for the hammer man.

Waves from each of these couplers were recorded using a three directional geophone and an Electro-tech Porta Seis. The signals were very weak even though they were recorded at distances of 10 to 50 feet. Different weight hammers were tried in an effort to improve the signal reaching the geophones. Just as it was best for the generation of compressional waves, the heaviest hammer was also best on each of the shear wave couplers.

The results as recorded by the three directional geophone and Porta Seis were ambiguous. The times seemed to be correct for the expected shear wave velocity, but approximately the same time was recorded on each of the three phones. At 20 feet, the time on the vertical phone should have been that of the compressional wave, about 16-18 msec, instead of 40-50 msec. A further complication was the failure of the transverse geophone break to reverse direction when the direction of the hammer blow was reversed. The breaks had high amplitude, which suggests the possibility of Rayleigh waves. The arrival times for shear waves and Rayleigh waves would have been very similar at these short hammer to geophone distances.

At this time it seemed that either the three component geophone was not registering the shear waves, the Porta Seis was not recording them, or the couplers were not generating them. Consequently, work was begun using the Huntec instrument and horizontal geophones. As a check, the same horizontal geophones were also used with the Porta Seis.

Most of the wave generating sources that had previously been used were tried again with the new geophones and the other instrument. Occasional success was achieved with both instruments when using the horizontal geophones and various energy sources. This seemed to indicate the couplers were generating shear waves. The best wave source was the 1-1/2 inch by 4 foot round bar struck with the 16 pound hammer. However, the large hammer usually knocked the bar loose and any subsequent blow created stronger compressional than shear waves. Tightening the bar by driving it deeper usually restored its ability to generate shear waves; but, the next blow would loosen it again.

A pendulum was then designed to generate shear waves. The pendulum consisted of a 2 inch by 6 foot round steel bar with a flat plate welded to the side. A hanger was located near the top from which the 16 pound hammer was suspended. The hammer head was lifted to some height and allowed to fall against the flat plate on the side of the bar.

The increased diameter of this bar made it much easier to keep tight in the ground; and the extra length allowed it to be driven in deeper. The results, however, were still sporadic. The bar had to be kept tight in the ground or the compressional wave became stronger than the shear. This had also been a problem with the other couplers that were tried. The plates might have worked if they had been cemented to a wall. When they were free to vibrate, each vibration generated a new wave train of predominantly compressional waves.

Shear waves were recorded at several locations using the Porta Seis recorder and horizontal geophones with the pendulum providing the wave source. Reversing the direction of the blow reversed the direction of break, showing that they were shear waves. The conclusion was that the Electro-tech Porta Seis could record and that the horizontal geophones could receive shear waves. The same phones were also used with the Huntec FS-3 to record shear waves. At least part of the initial failure to record shear waves must have been due to low output of the three component geophone, probably due to poor coupling between the geophone and the soil. The base plate of the three component geophone was not equipped with a planting spike. Instead, it used three short legs which had been designed for use on hard material and apparently did not effectively couple the geophone to soil, even though the geophone itself was quite heavy.

Most subsequent work was done with the pendulum and the Huntec instrument. The Huntec was used primarily because of the built in gain control, which allowed it to be operated at high gain while still displaying all arrivals. The results were still somewhat sporadic. The pendulum nearly always generated a compressional wave as well as a shear wave. If the bar was even slightly loose, the P wave would be stronger than the S wave. However, the pendulum was used to collect shear wave data from a number of areas.

The next type coupler used was an aluminum bar which measured 3 x 5 x 30 inches. The bar was laid normal to the seismic line and held in place by driving the truck wheel onto it, as shown by Figure 1. The bar was then struck on the end by swinging the hammer horizontally.

Because the bar is aluminum instead of steel, there is a better accoustic match between the coupler and the ground. There is also less high frequency compressional interference caused by ringing hammer blows. The bar is also better coupled to the soil and transmits a stronger S wave than other couplers that were tried.

Later work has been done using a wooden plank under the truck wheel. Only limited use has been made of the wooden plank and the results are still not known with certainty. It appears promising, but the life of the wooden plank has been very short.

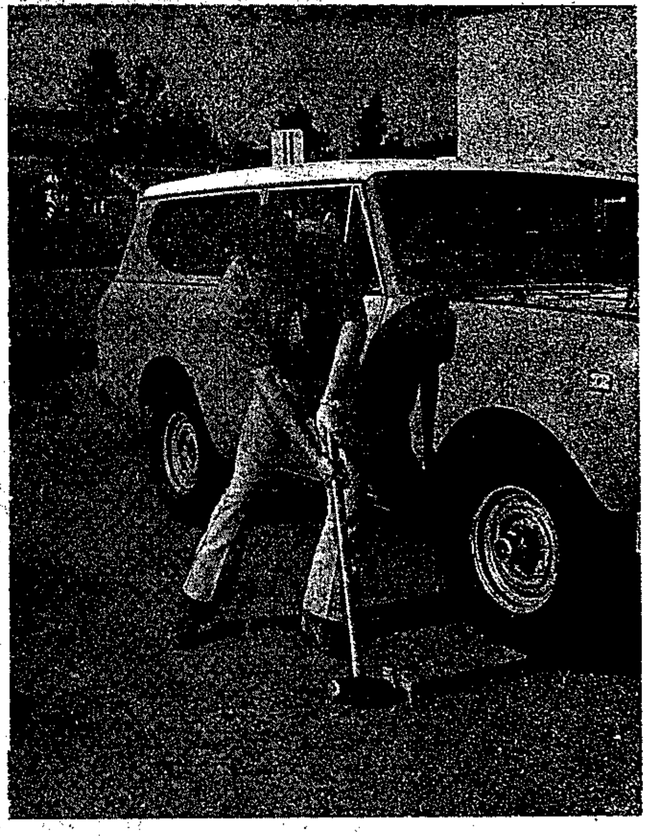


Fig 1 The aluminum bar laid normal to the seismic line and held in place by one wheel of the vehicle.

Explosives

Explosives are used as the wave source for much of our work, particularly where the depth of investigation exceeds 75 feet.

Several tests were made to determine the suitability of various explosives and, how to place the charge for maximum energy transfer consistent with other requirements such as safety. Types of explosives used were dynamite, ammonium nitrate and fuel oil (ANFO), 50 and 400 grains per foot primacord and kinepacs. These materials were classified as high or low velocity explosives, depending on the velocity of propagation of the explosive itself. The explosive material was packaged in different ways depending on the intended use. Typical uses would be as shaped charges, down hole shots or surface shots.

Most of our work is with material near the ground surface. This material transmits a shock wave at a velocity many times less than the velocity of propagation of even the slowest explosive. The resulting mismatch of acoustic impedance hinders energy transfer from the explosion to the soil.

The greatest transfer of energy occurs when the acoustic impedance of the explosive matches that of the soil. Because matching the two is rarely possible, the best procedure is to confine the explosion within the soil. This requires drilling a shot hole deep enough to confine the blast. Since a drill is often not available at the site, other methods have been used to produce adequate energy. A satisfactory amount of energy has been obtained using ANFO on top of the ground.

The noise from this type of shot is loud. However, by cleaning the immediate area around the shot beforehand, there is less danger of flying rock than from a shot which is covered by a thin layer of material but is not confined.

Tests were made to compare the energy transferred to the soil from surface charges, partially confined charges and completely confined charges. Both high and low velocity explosives were used in all three cases. The ANFO, with a propagation velocity of 13,800 ± fps was the low velocity explosive used. Primacord and kinepacs, both with a propagation velocity of 22,000 ± fps, were the high velocity explosives used. The amount of energy transferred was determined by measuring the amplitude of geophone placed at various distances of up to 600 feet from the shot.

The tests indicated very little energy transferred to the soil from a high velocity explosive shot on the surface. The exception to this was shaped charges which have a high velocity but are designed to direct energy into the soil. Our experiments with shaped charges indicates that they do transfer energy into the soil, but they are expensive, very loud, and often cause electrical interference on the seismic record. The electrical interference is a potential problem with all surface shots, but is worse with the high velocity explosives. The exact explanation for the phenomenon is not known, but it appears to be the result of an electrical disturbance in the air around the explosion. Burying the charge deeply enough to confine the explosion will prevent it. An electrically shielded geophone cable also prevented the interference.

The next tests used both high and low velocity explosives with shallow burial. Shallow burial is here defined as being a covering of soil that will be blown into the air by the explosion. Energy transfer was good from the low velocity explosive and poor from the high velocity explosive.

The next procedure tested was complete burial of the charge so that no material was blown into the air. Satisfactory energy was obtained from both high and low velocity explosives in this way. Unless the shot was buried in high velocity material (better acoustic impedance match), there was better energy transfer from the low velocity explosive than from an equal amount of high velocity explosive.

The ANFO is more bulky than the high velocity types and is, therefore, more difficult to bury. Results indicate an ANFO explosion propagates better when the charge has a compact shape, with the primer in its center. There is also a minimum of about 1 pound of ANFO that can be successfully detonated. These shape and size requirements make it very difficult to bury ANFO without drilling shot holes. Since a drill is seldom available at the field site, most ANFO charges have not been buried.

The 400 grain primacord, small sticks of dynamite on Kinepac sticks are relatively easy to bury in a hole made by driving a bar into the ground. These explosives were used very satisfactorily in such small diameter shallow holes. The hole was backfilled with moistened fine soil and tamped enough to form a solid plug. This method was particularly satisfactory when the energy requirement was not too great, as for shorter lines. By completely confining small high velocity charges in this way, they were used in close proximity to human activities without creating objectionable noise or hazardous flying debris.

Small buried charges of high velocity explosive did not give enough energy for long seismic lines when there was a considerable thickness of low velocity material. An equal weight of ANFO buried to the same depth would usually provide adequate energy.

ANFO can be obtained either ready mixed or as fertilizer and oil and mixed on the job. The ready mixed is more convenient to use but is more troublesome to transport and store. ANFO is not cap sensitive and requires a primer to set it off. Any high velocity cap sensitive explosive can be used as a primer. Commercial primers are available that have been designed especially for initiating an ANFO explosion. Nearly all of these are Class A explosives and are therefore troublesome to store and transport. Primacord is a Class C explosive so is much less trouble to use. It works well as a primer for ANFO, either in the 50 or the 400 grain size. The amount needed to do the job is a function of the amount of ANFO to be detonated. Our tests indicated two looped eight inch pieces of 50 grain for each 2-1/2 pounds of ANFO gave best results. Less than this amount often caused incomplete detonation, more than this amount tended to increase the velocity of the explosion.

Table 1 lists the different types of explosives and some of the advantages and disadvantages of each.

Explosives were used in attempts to generate shear waves on several occasions. No shear waves were recorded from explosions in borings in soft material either when the boring was open or backfilled. Shear waves were recorded from explosions in shallow borings in hard rock. These borings were lightly backfilled.

TABLE 1

Advantages and Disadvantages of Various Explosives

Explosive	Advantages	Disadvantages
Low Velocity		
Ammonium-Nitrate and Fuel Oil (ANFO)	1. Transported as fertilizer and oil. 2. Class C explosive. 3. Not susceptible to accidental detonation. 4. High energy transferred to soil. 5. Can be used on the surface or buried. 6. Inexpensive.	1. Difficult to place in small diameter borings. 2. Requires the use of a primer.
High Velocity		
Dynamite	1. Easily placed in small diameter borings. 2. Good energy transfer when confined.	1. Legal problems in transportation and storage. 2. Class A explosive. 3. Can cause headaches. 4. Low energy transferred to soil unless charge is confined. 5. Expensive.
400 grain Primacord	1. Class C explosive. 2. Not susceptible to accidental detonation. 3. Easily placed in small diameter borings. 4. Inexpensive. 5. Serves as Class C primer for ANFO.	1. Low energy transferred to soil, unless charge is confined.
Kinepac Sticks	1. Transported as two components, legally not explosives. 2. Not susceptible to accidental detonation. 3. Good energy transfer when confined. 4. Easily placed in small diameter borings.	1. Low energy transferred to soil unless charge is confined. 2. Expensive.
Kinepac Shaped Charges	1. Transported as two components, legally not explosives. 2. Not susceptible to accidental detonation. 3. Placed on surface, no boring necessary. 4. Moderate energy transfer.	1. Expensive. 2. Noisy. 3. Standard sizes usually too large for routine use.

Comparison of Hammer and Explosive Sources

A part of the investigation of wave sources was a comparison of results obtained from different sources. There was some question as to whether different sources created different waves which would then be recorded as having different velocities. Test lines were run at several different locations. Wave sources used were generated by high and low velocity explosives, both buried and on the surface, and by impacting a plate with a hammer. The lines using explosives as the wave source were recorded by either the Electro-tech Porta Seis or the Huntec FS-3. The hammer lines were recorded by either the Huntec or the Bison Model A. The length of the lines for comparing the hammer and explosives ranged up to 300 feet. When comparing high and low velocity explosives, the line lengths varied from 100 to 600 feet.

Some of the early tests did show a difference in velocities between hammer and explosion generated seismic waves. Time distance graphs which display the results of repeating seismic lines with different instruments or different wave sources are shown in Figures 2 and 3. As discussed in the section under instruments, tests were first conducted to determine the accuracy of the instrument timers. These tests determined the timers to be much more accurate than the differences in arrival times.

Tests were then conducted with the Electro-tech using explosives of different propagation velocities, both on the surface and buried. There was an obvious difference in the amount of energy reaching a geophone at moderate distance from the different explosions. In all cases, the most energy was from the buried low velocity explosive, and the least from the surface shot of high velocity explosive. However, the arrival times and the wave velocities were the same.

The amplitude of a geophone break from an explosive source was then compared to the break from a hammer source. No quantitative measurements were made of the two breaks, but estimates were made of their relative magnitude. At any wave source to geophone distance, the difference in signal strength of the explosion generated source compared to the hammer generated source was several orders of magnitude. The blasting cap alone generated almost as much energy as the hammer for the first 50 to 75 feet.

The hammer lines were then repeated using a higher gain setting on the amplifiers. As shown by the time distance graph in Figure 4A and 4B, when the gain had been increased to a high enough level, the hammer line duplicated the explosive line. The condition was then checked several times using both explosives

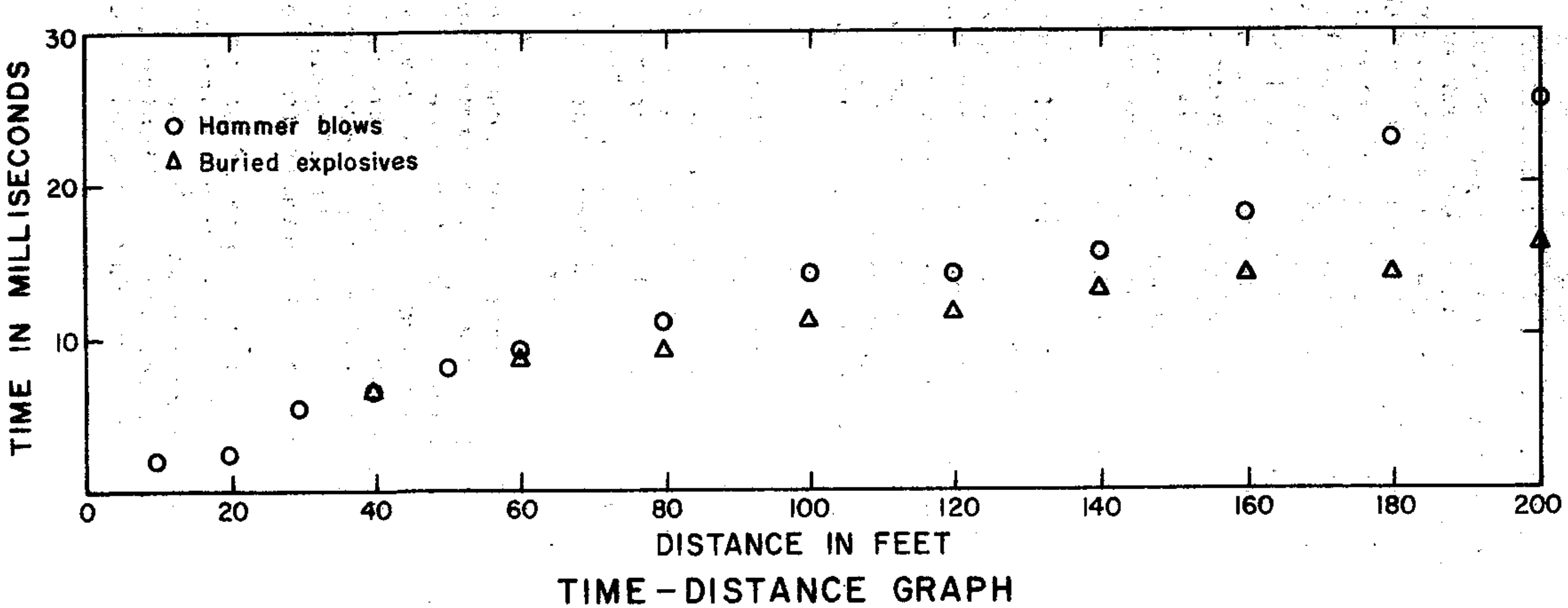
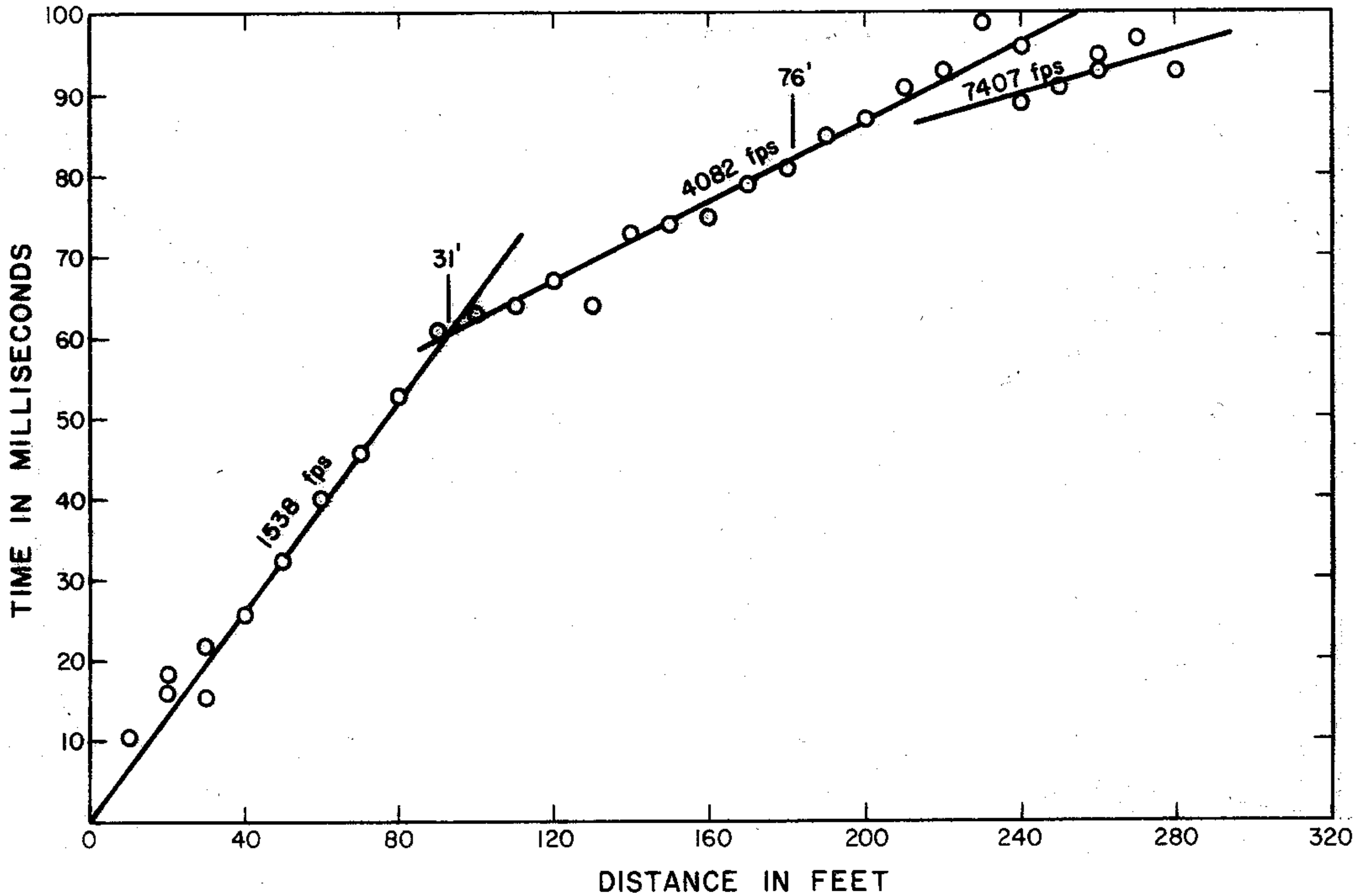
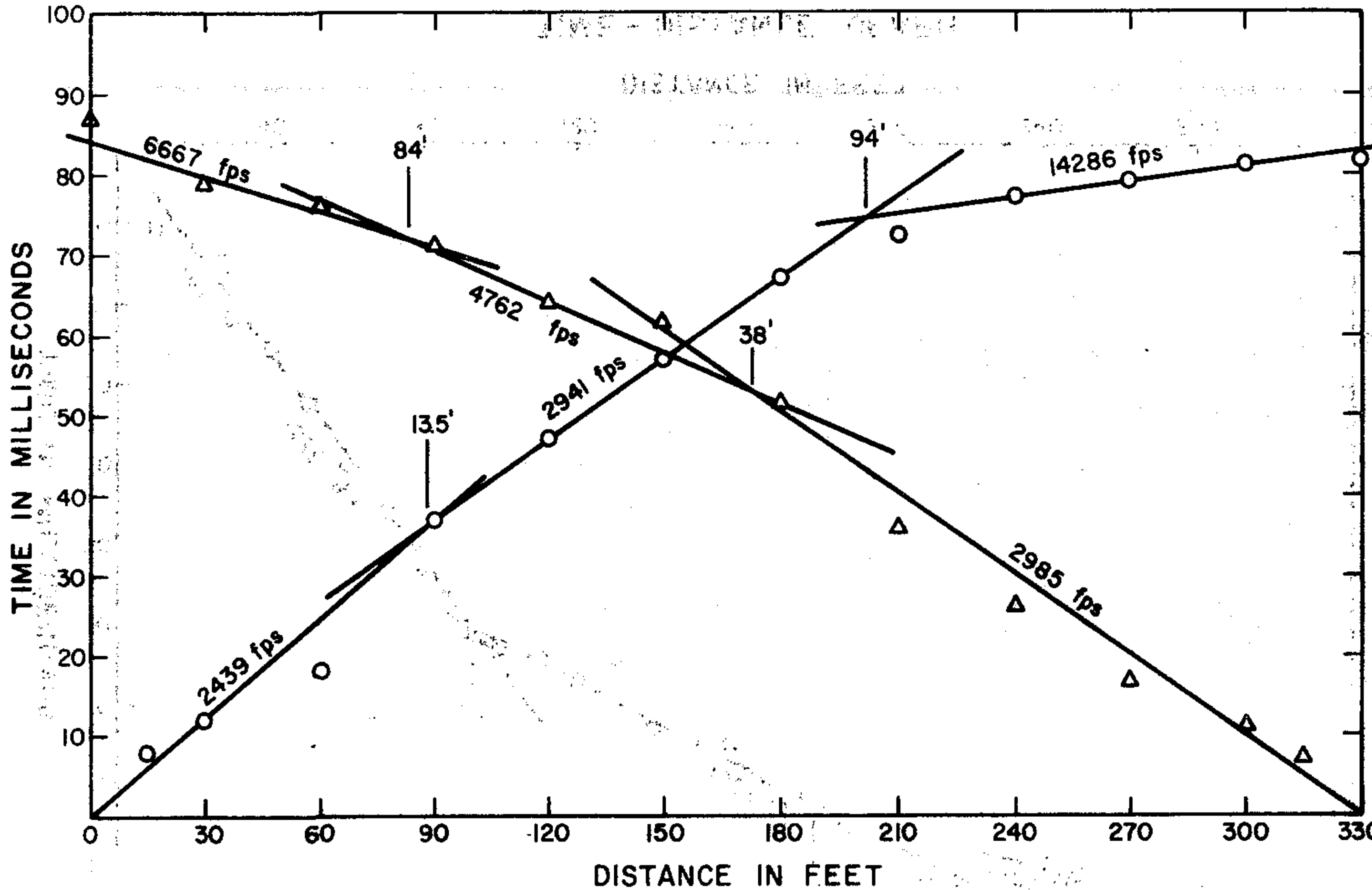


Fig 2 A time-distance graph showing different arrival times from hammer and explosive sources. Both were recorded by the Huntec instrument.



TIME - DISTANCE GRAPH

Fig 3A A time-distance graph showing arrival time as measured by the Bison, using a hammer to provide the energy.



TIME - DISTANCE GRAPH

FIG 3B Same location as 3A. This record obtained with the Electro-tech using explosives.

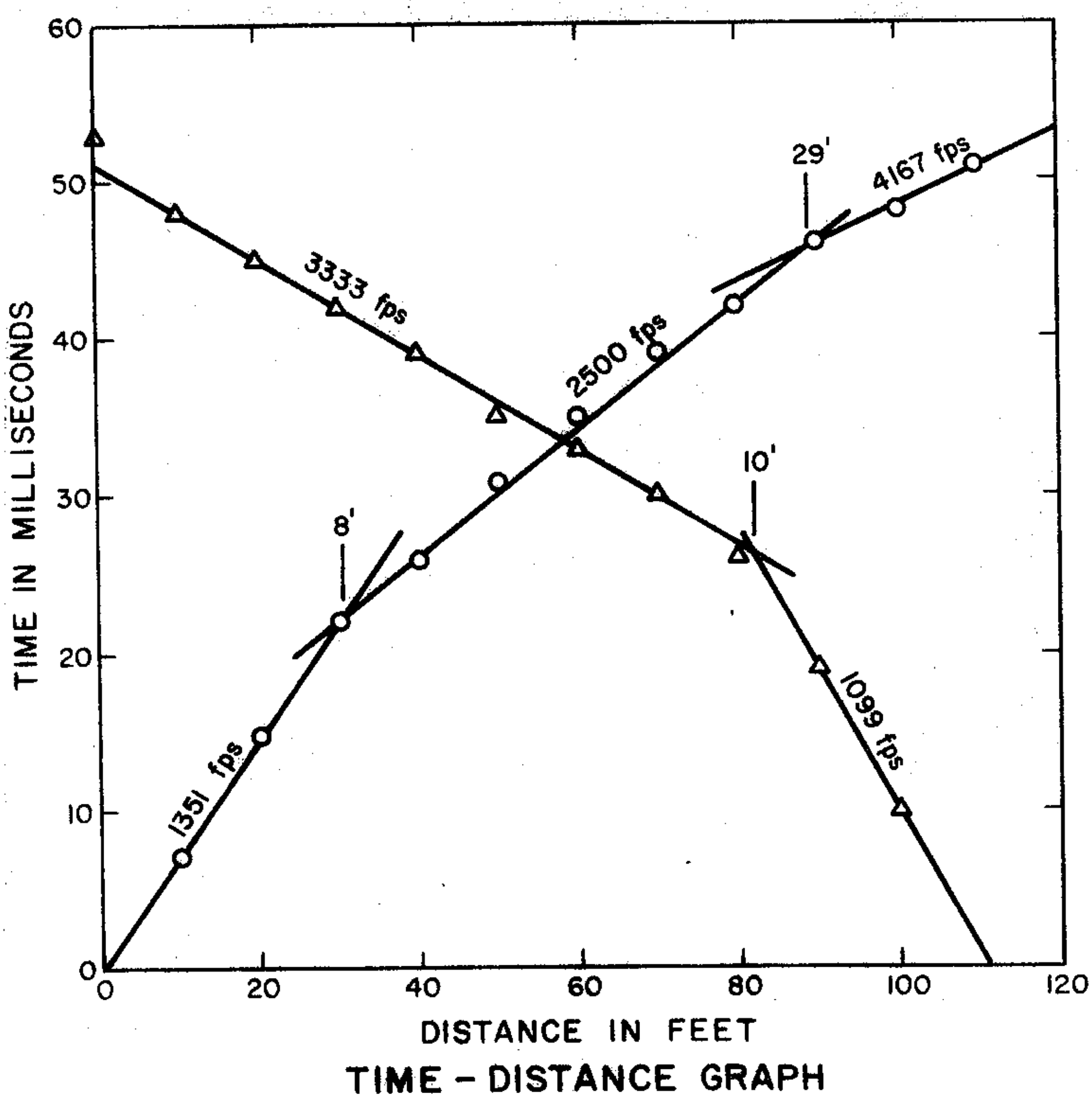
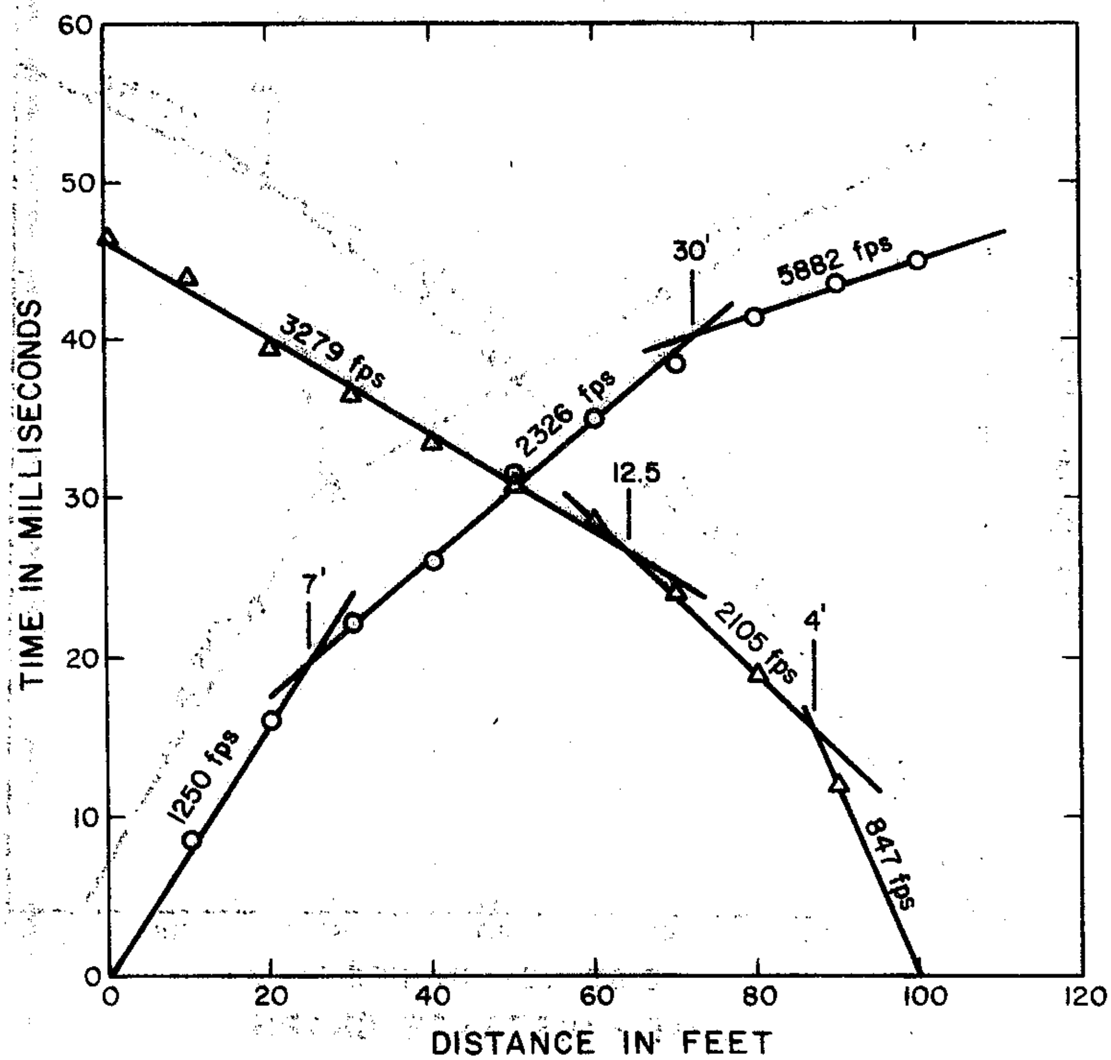


Fig 4A A time-distance graph using data obtained with the Electro-tech using explosives.



TIME - DISTANCE GRAPH

Fig 4B Time-distance graph of hammer blows recorded by the Bison at the same location as 4A. This line was 10 feet shorter than 4A.

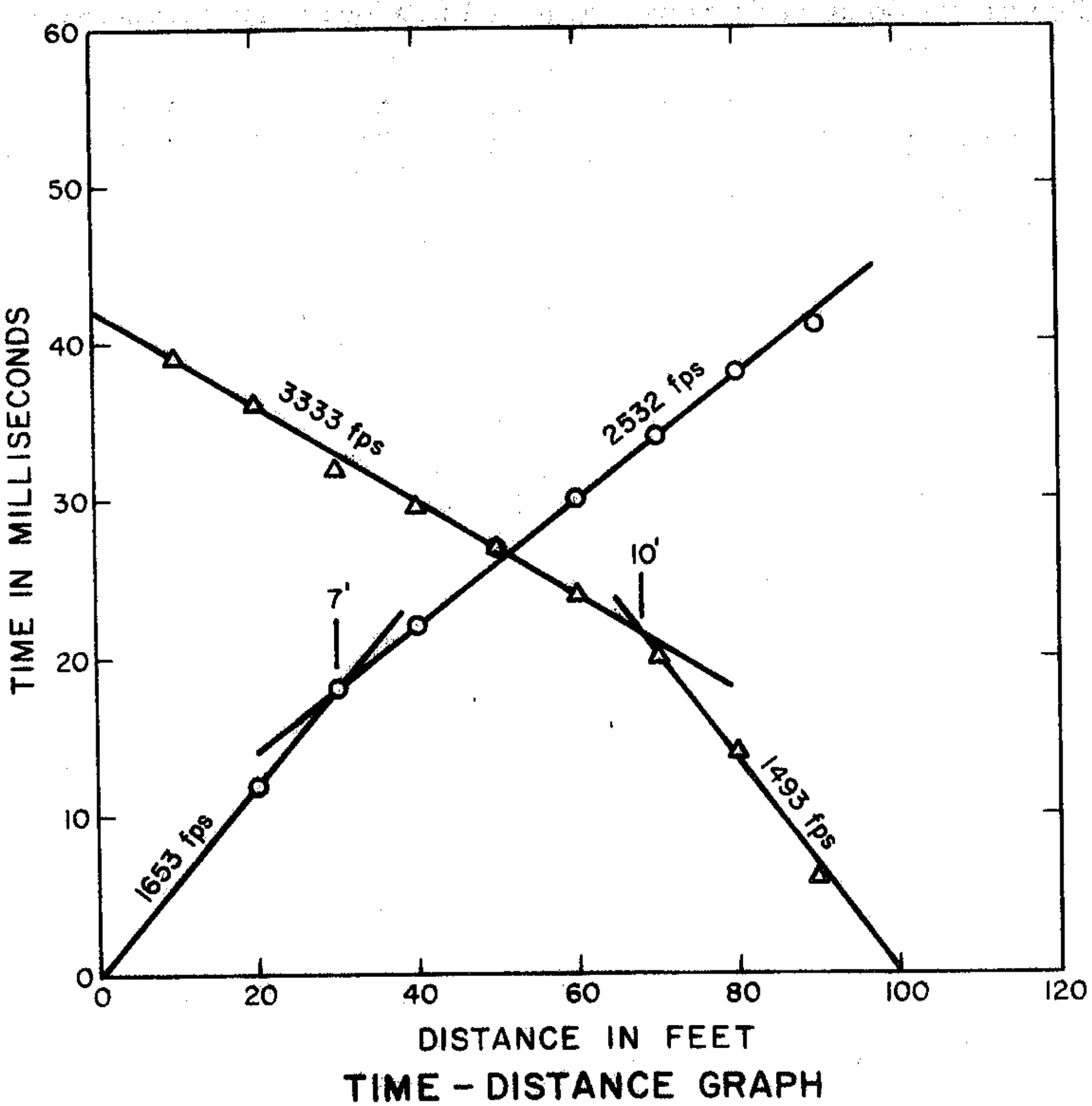
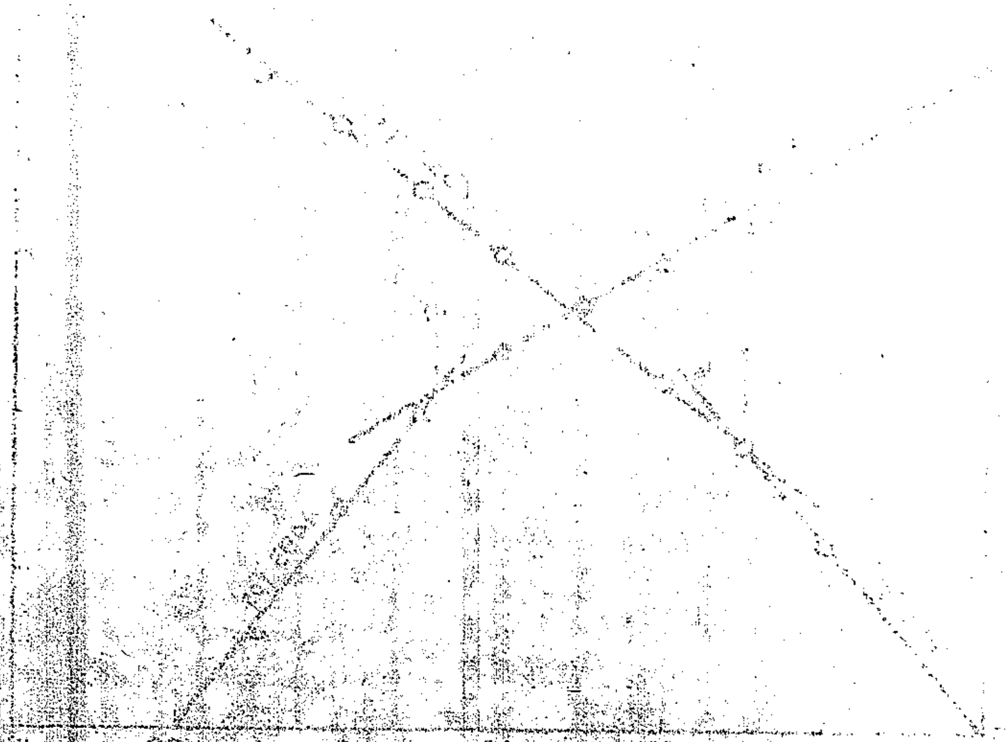


Fig 4C. Time-distance graph of hammer blows recorded by the Huntec instrument. The same geophones were used for the lines shown in 4 A, B and C. No changes were made in geophone polarity for the different instruments, which accounts for this record being 1/2 cycle faster (about 4ms) than the others at any equal distance.

and hammer on the Electro-tech and Huntec and the hammer on the Bison. On all three instruments, the gain had to be set high enough to record considerable noise to be sure of recording the first arrival from a hammer blow. It was also necessary to repeat readings to be sure random noise events were not mistaken for first arrivals.

The conclusion from these tests was that at the length of line used, the velocities were the same for all wave sources.



WAVE DETECTORS

Testing of the wave detectors began with the testing of wave sources. Additional detector testing was performed later using the wave sources considered best for each specific purpose.

The first of the detectors to be tested was the three component geophone. It consisted of three Mark L-10 elements, each oriented along one of the three mutually perpendicular axes. The elements were mounted inside a metal case so the complete geophone could be used either on the surface or in a boring. A screw-on base plate provided three point contact with the ground surface.

Testing of the three component geophone was done during the first attempts to record shear waves from different wave generating sources. The recorded wave arrivals were not consistent and made interpretation of the results ambiguous. As stated in the section under shear waves, the problem was determined to be low output of the three component geophone, probably due to poor coupling between the geophone and the soil.

Since positive results were not obtained with the three component geophone, it was necessary to use other detectors to determine the effectiveness of the wave sources. The other detectors were also Mark L-10 phones, but were the regular vertical and horizontal geophones. There were twelve of each, equipped with clips for use on a takeout cable. They were used with both the twelve channel Electro-tech and the two channel Huntec instruments.

Since the phones were the clip on type it was possible for them to be interchanged between positions on each different seismic line. The phones were therefore numbered in order to maintain a record of where each was being used. The geophone number was then recorded along with other data for the line. This enabled the operator to identify phones which performed differently than others of the group.

One of the findings of these tests was the extreme variability between different geophones with the same nominal specifications. It was not unusual to choose two geophones from the group and find them different in nearly every aspect of their performance. The output of one might be four to five times as much as the other. An even more serious problem, especially with the horizontal phones, was phase shift. The Huntec instrument has two channels; although it only records one at a time. A correlator circuit makes it possible to combine the two incoming signals if both are in phase. There is a single gain control for both channels. If the output of the two geophones differs greatly, the signal will not be amplified enough to be seen by the instrument. Consequently, it was necessary to have two geophones with output to be used with the correlator circuit. This sometimes involved much trial and error comparison to get two geophones with matched output.

The regular vertical and horizontal geophones did record compressional and shear waves from several of the wave generating sources. This was accepted as evidence that the original problem had been with the three component geophone.

The horizontal geophones had an impedance of 374 ohms and a natural frequency of 8 Hz. They were equipped with tapered blade shaped planting devices and a bulls eye level bubble. The blades were difficult to plant in the ground, and were judged to be less effective than round spikes for coupling the geophone to the soil.

The coils in horizontal geophones are suspended at each end instead of only at one end as is the case with vertical phones. When the phone has been properly planted using the level bubble, the coil is suspended and is free to respond to any movement. Consequently, horizontal phones are very sensitive to any wind or airborne noise. One method of improving the situation was to bury the phone. However, burying the phone did not prevent it from receiving airborne noise which was transmitted through the soil covering. The covering did protect the phone from being hit by blowing sand or vegetation and prevented the wind from causing the phone to vibrate.

Orientation of the geophone was important. Normal procedure was to orient the phone normal to the seismic line to record horizontally polarized shear waves (SH waves). The hammer was then swung parallel to the length of the geophone. Reversing the direction of the hammer blow or reversing the geophone would cause the shear wave to break in the opposite direction. These methods were used routinely to determine if the recorded signal was a shear or compressional wave. Figure 5 shows a diagram of the field arrangement and an illustration of the behavior of the wave forms.

At one location, horizontal geophones were used to record horizontally traveling compressional waves. The site was a vertical wall in an underground mine. For this use the horizontal planting devices were removed and vertical spikes put in their place. Horizontal holes drilled into the rock face provided horizontal plants for the geophones. The wave source was a shaped charge placed against the face of the wall. Records were good and had velocities that agreed with those obtained in the same material by conventional refraction lines. A four inch stream of water was falling from a height of 40

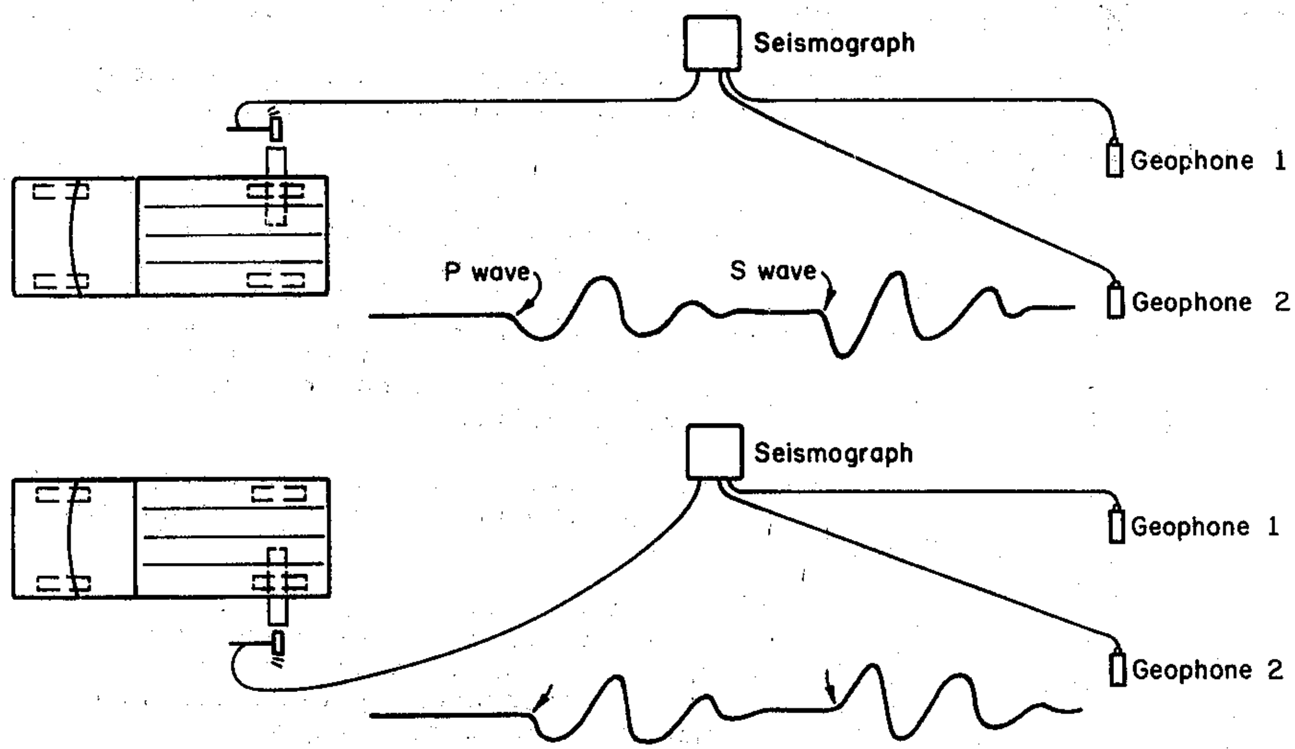


Fig 5   A schematic plan view showing the relationship of the truck, coupler and horizontal geophones. The two views show the two blows in opposite directions necessary to determine if the wave exhibits reversal with reversed hammer direction. A seismic wave form is shown for each hammer blow. The geophones are on each side of a centerline projected through the hammer positions.

feet to the mine floor about 15 feet from the wall. A geophone in the wall about 5 feet above the floor was not affected by the noise of the water.

A comparison was made between the output of the vertical L-10 geophones and other vertical geophones of different coil size. The other geophones were the Mark L-1 and L-9, and the Hall Sears HSJ. Each geophones output was determined by measuring the amplitude of the first break. The amplitude of the breaks of the L-9 and HSJ appeared identical to the unaided eye. When they were measured under low power magnification, the L-9 breaks were consistently of greater amplitude.

The L-10 geophones could be seen to have nearly 50% more amplitude than the L-9. These particular L-9 geophones have also required more repairs than the L-10 geophones.

The L-1 had almost three times as much output as the L-10. However, the L-1 was also more than three times as heavy which made it too heavy to be permanently attached to the cable. Additional cables with L-10 geophones permanently attached have been purchased, and are being used as standard equipment.

An investigation was also made of the effect of the geophone impedance on the output as measured by the amplitude of the break. According to our calculations, the best impedance match for the Electro-tech would be a little less than 500 ohms. The impedance of the geophones in stock at the beginning of the study was 280 ohms. The standard impedance of available geophones that came closest to 500 ohms without exceeding it was 374 ohms. A comparison was made between geophones having 280 and 374 ohms impedance, but no measurable difference could be detected. A comparison was then made between geophones having natural frequencies of 4.5, 8, 14, 20, 28 and 40 hertz. These tests were repeated several times at distances of up to 600 feet from the wave source. The phones were evaluated on the basis of the amplitude of geophone break, ease with which the break could be picked and the apparent accuracy of the time pick.

As shown in Table 2, the 4.5 Hz phone usually had the highest output, with the 8 Hz phone being a close second. The break of the 8 Hz phone was usually sharper than the break of the 4.5 Hz phone. When the geophone frequency was higher than 8 Hz, the breaks were sharper but the amplitude became less. At most wave source to geophone distances, the 8 Hz geophone break was the easiest to pick for the exact instant of arrival time. Since our refraction lines are nearly always less than 600 feet in length, it appears the 8 Hz geophones are the best choice for use with our present equipment.

Table 2
Signal Amplitude with the Geophones at Various Distances from the Shot.

Amount and type of Explosive	Shot to Geophone	Geophones, and Amplitude of break in inches 4 Hz	8 Hz	8 Hz	14 Hz	20 Hz	28 Hz	40 Hz	Arrays, individual geophone impedance of: 90	374	1200
4 inches Primacord	100 feet	1.43	1.4	.75	1.3	1.15	.98	1.03	too great to measure		
1 1/4 LB ANFO	100 feet	Amplitude too great to measure									
8 inches Primacord	200 feet	0.5	0.4	0.28	0.42	0.28	0.32	0.28	0.85	0.85	0.88
1 1/4 LB ANFO	200 feet	2.28	2.18	---	2.07	2.9	1.8	1.65	too great to measure		
8 inches Primacord	300 feet	0.22	0.18	0.13	0.18	0.15	0.15	0.13	0.4	0.37	0.4
1 1/4 LB ANFO	300 feet	1.25	1.12	0.8	1.03	0.87	0.78	0.67	too great to measure		
12 inches Primacord	400 feet	Too weak to measure							0.1	0.1	0.08
18 inches Primacord	400 feet	Too weak to measure									
1 1/4 LB ANFO	400 feet	0.13	0.14	0.08	0.13	0.12	0.1	0.07	0.23	0.23	0.25
1 7/8 LB ANFO	400 feet	0.15	0.15	0.12	0.13	0.13	0.1	0.08	0.3	0.32	0.28
1 7/8 LB ANFO	400 feet	Too weak to measure (this charge was on the ground surface)									
24 inches Primacord	500 feet	Too weak to measure							0.1	0.08	0.1
2 1/2 LB ANFO	500 feet	0.25	0.23	0.17	0.22	0.18	0.17	0.13	0.43	0.42	0.45
36 inches Primacord	600 feet	Too weak to measure							0.07	0.07	0.06
2 1/2 LB ANFO	600 feet	0.22	0.25	0.17	0.17	0.2	0.14	0.23	0.32	0.28	0.3

The amplitudes of the first breaks for the different geophones are shown with various shot to geophone distances. The shots were of the indicated amounts of either 400 grain Primacord or ANFO. All shots were buried except the one indicated.

The two 8 Hz geophones indicate the possible variations in response from supposedly

Three geophone arrays were purchased and tested. Each array consisted of four Mark L-10 geophones permanently attached to the cable with 4-1/2 feet between phones. The arrays were wired differently using geophones of different impedance, but with the input impedance to the recorder nearly the same for each array. One set was wired in series using geophones with an impedance of 90 ohms. The second set was wired in parallel series using geophones with an impedance of 374 ohms. The third set was wired in parallel using geophones with an impedance of 1200 ohms.

The arrays were compared with each other and with various single geophones. No problems were encountered with geophones not functioning during use. Therefore, no evaluation was made of the best wiring arrangement to use in the event failures took place. The comparisons were made using either the Electro-tech or the Huntec to record the signals. The wave source to geophone distance varied from 30 to 600 feet.

There was no consistent best array. No single array would consistantly show a higher amplitude break than the others. The possiblity that this was a function of distance from the wave source or of length of geophone cable was investigated. However, the data was not consistent enough to provide a definite answer. It was established that differences existed between different amplifiers and galvanometers in the Electro-tech. It is possible the apparent differences between the arrays was the result of differences in the Electro-tech recording system.

The comparison of the arrays with the single geophones showed the arrays to have greater output than single HSJ, L-9, L-10 and L-15 phones. The arrays were about equal in output to the L-1 geophone. At short distances, a stronger signal was received from the arrays if the four phones were clustered. At greater distances, there did not seem to be much difference.

At short distances, an array could cause signal cancellation if the geophones were spread and the material had a low seismic velocity. Since the phones were only 4-1/2 feet apart, the ability to cancel signals with one array was limited. However, when two arrays were used with the correlator circuit of the Huntec, the distance between the two arrays could be chosen to either enhance or cancel signals. This principle was usually employed when using the Huntec instrument. For refraction lines, the two arrays were placed a calculated distance apart normal to the direction of the seismic line. This placed the two arrays equidistant from the hammer station. Any signal from the hammer should arrive in phase and be enhanced. Noise arriving from the side would be out of phase and cancelled if the proper spacing had been chosen.

This method of signal cancellation was the basis for the attempts to record shallow reflections. The geophone arrays were used with an arrangement designed to cancel refractions and enhance reflections.

ELECTROMAGNETIC INTERFERENCE

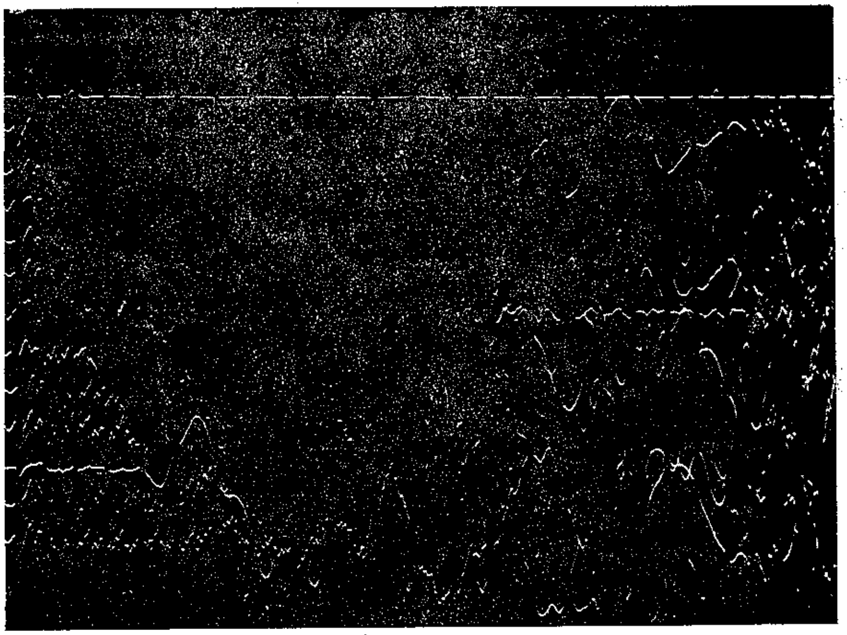
There are a number of areas within the state where high frequency electromagnetic energy interferes with normal seismic investigations. At times the level of this noise is high enough to completely mask the desired signal and make seismic recording impossible as shown by the record in Figure 6. An effort was made to find a way of getting good records in these areas.

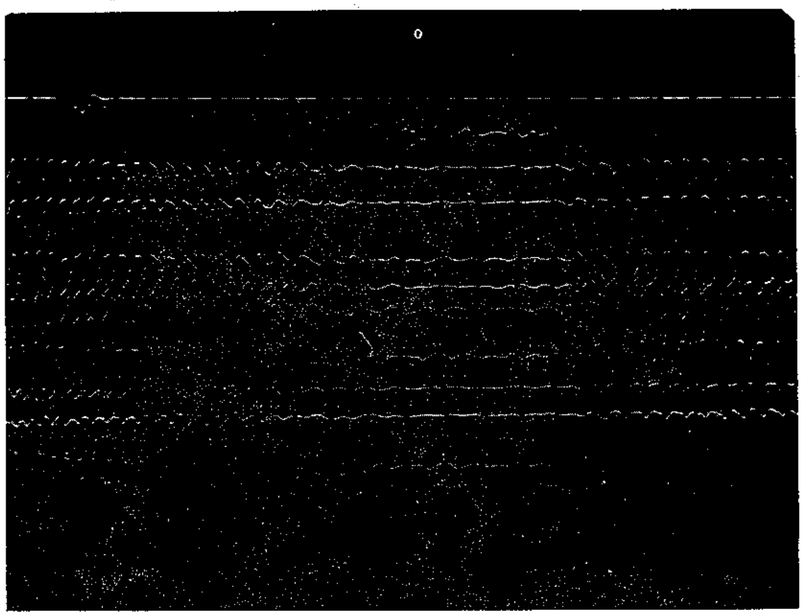
Testing was done using an Electro-tech instrument and a takeout geophone cable. Noise was present on the record either with or without geophones on the cable. The noise disappeared from the record when the cable was disconnnected. The cable was then connected to an oscilloscope so the level of the noise could be monitored while the cable was rotated a full 360° around the instrument. The level of the interfering noise varied as the cable was rotated, with 90° between high and low readings. The conclusion was that the cable was acting as an antenna and receiving high frequency electromagnetic energy.

The geophone cable was then electrically shielded using aluminum tape. The outer end of the cable was not grounded while the instrument end was grounded through the instruments grounding terminal. No noise was present on the record when the shielded cable was used. The record in Figure 7 was taken at the same location and nearly the same time as the one in Figure 6A. The only difference was the shielded cable used to obtain the record shown in Figure 7.

Following this experiment a cable was purchased which had shielding built into it. Additional tests using both shielded and unshielded cables confirmed that good records could be obtained with the shielded cable where the records were useless when an unshielded cable was used. Shielding the cable also prevented interference from 60 cps and from surface explosions which created crossfeed on all traces.

The shielded cable is heavier and stiffer than a regular cable, so is less convenient to use in the field. Being stiffer, the cable is more likely to be kinked, resulting in breakage of the shielding or one of the conductor wires, for these reasons, the working life of our shielded cables has been only a small fraction of the expected life of an unshielded cable. The short life makes these cables very expensive to use since the original cost is almost twice as much as an unshielded cable.





B

Fig 6A and 6B. Seismic records showing electromagnetic interference.

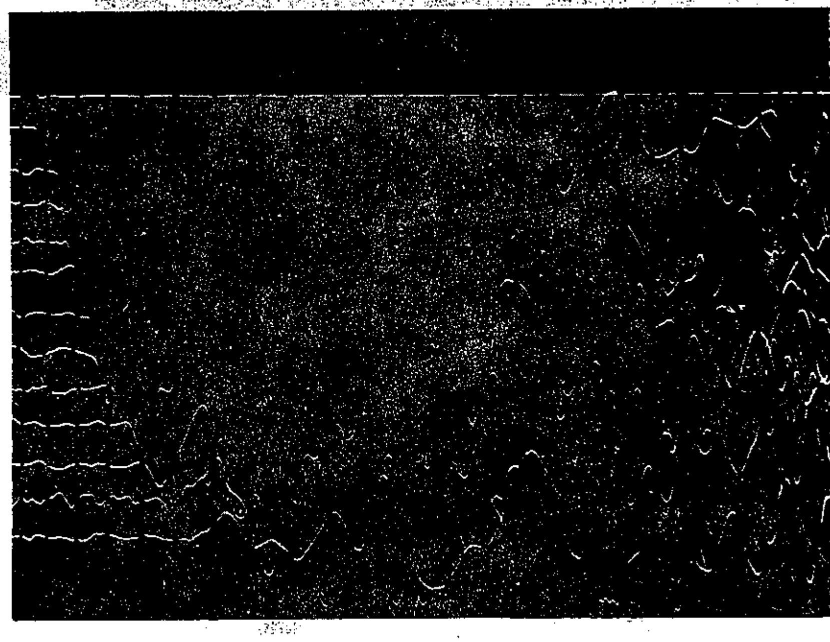


Fig 7 Seismic record of the same line as in Fig 6A.
This record obtained using the shielded cable.

INSTRUMENTS

Four different seismic instruments were used in the course of this study. These were the Electro-tech Porta Seis, the Bison Models A and B, and the Huntec FS-3. The Geochron and MD-3 had been used previously and the experience gained from their use was incorporated into the study.

The Electro-tech Porta Seis had been used by this department for several years for recording refracted compressional waves. The other three test instruments were purchased by this Department during the course of the study. All three were single channel recorders designed primarily for use with a hammer. A complete description of each of the instruments used during the study is given along with a picture of each.

Electro-tech

The Electro-tech Porta Seis is a portable, self contained twelve channel instrument designed primarily for use with explosives. Each channel has a transistorized amplifier and rotating mirror galvanometer. The galvanometer mirrors are deflected proportionately to the signal voltage from the amplifiers. An internal light beam is projected onto the mirror in each galvanometer from where it is reflected through a series of mirrors to a polaroid film. A pendulum and rotating mirror provide the motive force to sweep the reflected traces along the record. When the pendulum is released at the time of firing, it starts the vibrating reed timer, which interrupts each light beam at 10 millisecond intervals. Releasing the pendulum also releases a microswitch which discharges the blasting capacitor and registers a time break on the timing trace. A permanent record of the results of each shot is provided by the polaroid film.

One of these instruments has been in use by this Department since 1963 and a second one was purchased in 1967. The second instrument had some minor improvements but was basically the same intrument with the same electronic components. Figure 8 is a photograph of one of the Electro-techs.

Huntec

The Huntec Model FS-3 is a single channel fascimile seismograph. It was designed primarily for use with a hammer, but can be used with explosives if necessary. The instrument has two receiving channels and can record through either of them. It also has a correlator circuit which allows coincident signals from both channels to be recorded. The gate width of the correlator is adjustable and allows the operator to choose how much phase

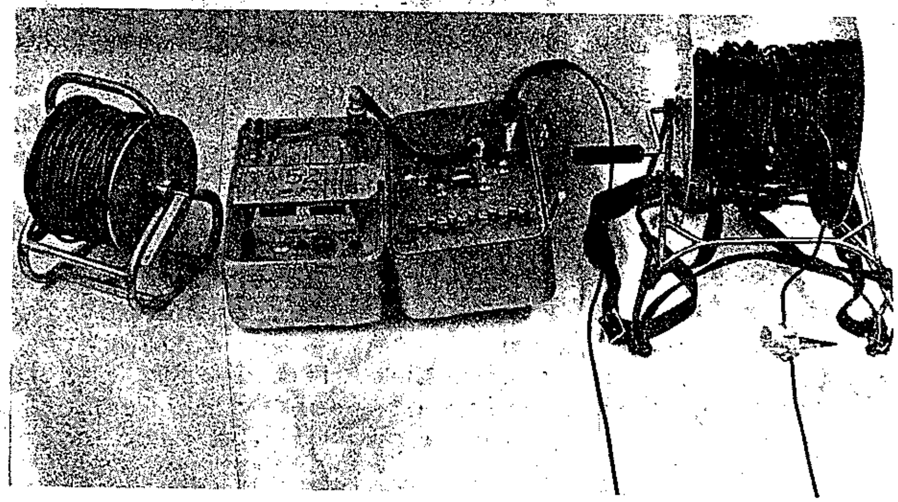


Fig 8 Photograph of the Electro-tech ER-75-12. The shotline is shown on the left and the geophone cable on the right. A film packet is lying across the instrument.

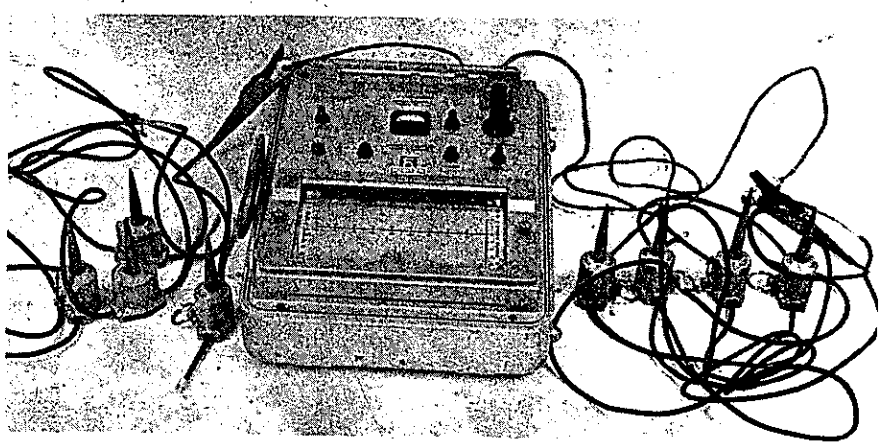


Fig 9 Photograph of the Huntec FS-3 and two of the 4-geophone arrays.

difference will pass through. An internal gain control enables the instrument to record the entire waveform. The record is shown as a series of short dashes across a continuous strip chart. The chart can be advanced an amount that is proportional to the hammer spacings and a time distance graph drawn directly on it.

Bison

The Bison Models A and B are single channel seismographs designed for use with a hammer. Both instruments digitize the incoming waveform and store it in electronic memory. The digitized signal is displayed on a cathode ray tube. First arrival time is picked by moving a marker pip to coincide with the first break. The time corresponding to the pip location is then displayed in digital form on the face of the tube. A quartz crystal is used as the timer.

The Model A is an earlier model no longer in production. It digitizes the waveform using 100 bits along the horizontal axis and 16 bits on the vertical axis. Figure 10 is a picture of this instrument.

The current Bison instrument is the Model B, which has a number of improvements over the earlier model. The major change has been an increase in the number of increments used to digitize the waveform for storage. This model uses 256 bits on each axis. This instrument is shown by Figure 11.

The complete waveform from the electronic memory is displayed on the face of a cathode ray tube. Each succeeding waveform is algebraicly added by the memory unit and again displayed on the screen. This allows the operator to enhance the desired signal and eliminate random noise by repeating hammer blows.

A number of field and laboratory tests were made of all instruments to determine some of the capabilities and limitations of each. Field testing usually included the testing of accessory equipment as well as the seismographs. In some cases, the testing was a comparison between instruments and in other cases was an evaluation of a particular item with one instrument.

One of the tests of the Electro-tech was to determine what effect different frequencies of input signal would have on the amplitude of the recorded signal. The input voltage to the instrument was monitored on an oscilloscope and kept at a constant level. Results of the cumulative effect of the instrument's amplifiers and galvanometers were shown on the film. The results show a variation of about 8% in the output of the amplifiers used.

Fig 10 Photograph of the Bison Model 1570A

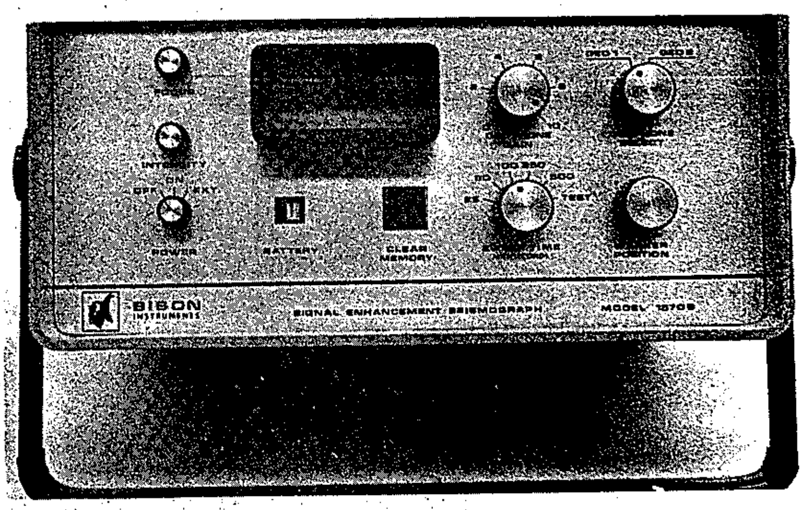


Fig 11 Photograph of the Bison Model 1570B

Not all of the channels were used in this test, but later testing of other channels gave similar results. This results of the test, as shown in Table 3, show the amplifier-galvanometer combination of this instrument has its greatest gain in the 30-35 Hz range. This is also the frequency range of high output from the 8 Hz geophones used by the Department. According to available literature, this frequency is in the range of most refracted seismic waves.

A second test of the differences between amplifiers was then made using the same instrument. The output of each channel was compared using a constant 30 Hz input signal. The results are shown in Table 4. A comparison of amplitudes from a common geophone input was then made which indicated the difference between adjacent channels may be as much as 10-15%.

In the section under wave sources compared, there is a discussion of the difference in arrival times between explosion generated seismic waves and hammer generated seismic waves. The first tests did show different arrival times. Additional testing was then done to determine why such a difference existed. Part of the additional testing was a test of the timers in the instruments to determine their part in the final result.

The instrument timers that were tested were those in the two Electro-techs and the two Bisons. A comparison of arrival times was made to determine the accuracy of the Huntec relative to the other instruments. This comparison indicates the Huntec has an accuracy comparable to the Bison instruments.

The timer test used a pulse generator to generate a square wave with a half wave length of exactly 10 milliseconds, as measured by the largest scale on an oscilloscope. The signal was fed to each instrument in turn by means of the geophone input. The length of each half of the square wave was measured using the marker pips on the cathode ray tube of the Bison instruments. It was measured on the polaroid film for the Electro-tech instruments. If the timers in each instrument had been perfect, each half wave length would have lasted exactly 10 milliseconds.

As can be seen by Table 5, the quartz timers used in the Bison instruments are extremely accurate. The times shown on the Model A are perfect. There was a jump of one digitized bit at about 0.6 of full scale on the Model B. This jump represents 1/256 of the full scale. On the 100 millisecond sweep, one bit is 0.4 of one millisecond.

The signal to each Electro-tech was split and recorded on three separate channels. There was little difference between the two Electro-techs. Table 6 shows the results of one of them. Both

Table 3

Amplifier Response - Electro-tech

Input Frequency	Output Amplitude (inches)	
H_2	Channel 1	Channel 12
2	0.0	0.0
5	0.40	0.40
10	0.65	0.80
15	1.0	1.10
20	1.0	1.20
25	1.10	1.25
30	1.25	1.30
35	1.15	1.30
40	1.15	1.25
200	0.80	-

The amplitude of the output signal is shown for a constant amplitude input signal at different frequencies. Only the two channels shown were used.

Table 4

Amplifier Response- Electro-tech

Channel	Output Amplitude (inches)
1	1.25
2	1.30
3	1.25
4	1.20
5	1.25
6	1.30
7	1.20
8	1.25
9	1.25
10	1.25
11	1.25
12	1.30

A comparison of the output of each channel using a constant amplitude 30 Hertz input.

Table 5

Tests of the Instrument Timers

Bison Model 1570A

Sweep Time and Recorded Arrival Times

20 ms Sweep	50 ms Sweep	100 ms Sweep
1.8 ms	7.0 ms	4.0 ms
11.8 ms	17.0	14.0
	27.0	24.0
	37.0	34.0
		44.1
		54.0
		64.0
		74.0
		84.0

Bison Model 1570B

Sweep Time and Recorded Arrival Times

50 ms Sweep	100 ms Sweep
2.5 ms	3.8 ms
12.5	13.8
22.7	23.8
32.7	33.8
42.7	43.8
	54.2
	64.2
	74.2
	84.2
	94.2

Table 6

A single incoming signal was split three ways and recorded on each of three Electro-tech Channels.

Electro-tech ER-75-12

Channel number and recorded arrival time

1	3	5
0 ms.	0 ms.	0 ms.
10	10	10
20	20	20
31	30	30
41	40	40
52	51	50
62	61	60
72	71	70
82	81	81
92	91	91
102	101	101
112	111	111
122	122	122
132	132	132
142	142	142
153	152	152
162	162	162
173	172	172
182	182	182
192	192	192
202	202	202
212	212	212
222	222	222

These tests were made to determine the accuracy with which each instrument registered a timing signal with a period of 10 milliseconds. The recorded arrival times should be exactly 10 milliseconds apart.

of them were slightly less accurate than either of the Bison instruments. However, for practical purposes, there was no significant difference between the different timers.

This test was undertaken to determine the accuracy of the timers in the Electro-tech and Bison instruments, as a way of resolving the difference in their recorded arrival times. As shown by Tables 5 and 6 the Bison times should have been fastest, if all instruments were recording first arrivals. The conclusion from the series of tests was that the slower times shown by the Bison and Huntec instruments, from hammer sources, were not first arrivals. Repeating the same lines with significantly higher amplifier gain did record first arrivals on all instruments. The first arrival times were then the same on any instrument.

Table 6 also shows a difference between channels of the Electro-techs. The generated pulse was common until it was split to each of the three amplifiers. The light beam that reflected off the galvanometers was a common beam. If it is assumed the time picks were accurate, the difference has to be explained by differences in the amplifiers or galvanometers. A difference in amplification between amplifiers had already been determined. There could also be a difference in rise time, but this was not tested.

The probable explanation for the difference is misalignment of the galvanometers. The vibrating reed timing mechanism interrupts the light beam between the light source and the galvanometers. If the galvanometers are out of alignment, the time interruption on each trace will be shifted according to the amount that galvanometer is out of alignment. In measuring the arrival time of a seismic wave on each trace, allowance is made for any detectable misalignment. The discrepancy between channels on this test was small and could be the result of undetected misalignment.

Misalignment is a potential problem with all multi-channel recorders which record by means of deflecting galvanometers. It would be completely undetected on any instrument with a single zero time and a common interruptor for all traces.

SEISMIC TECHNIQUES

Five seismic techniques were investigated to determine possible application to the solution of highway design and excavation problems. For the technique to be useful, it must be one that related to the geology or correlated with a method that related to the geology.

The refracted compressional wave and uphole methods had been in use by this Department for several years prior to the study. The other three, refracted shear waves, hammer reflections, and surface waves had not been used, but were investigated to determine their usefulness.

REFRACTED COMPRESSIONAL WAVES

Refracted compressional waves were recorded as part of the process of testing wave sources and detectors or as a check on one of the other recording techniques. As more expertise was developed in generating and recording the different wave forms, the quality of the compressional records was also improved. As improvements were developed they were incorporated into the routine work.

Lines were run specifically for the purpose of recording compressional waves only when an unusual situation occurred. One of these was the desire to record compressional waves traveling horizontally in a vertical wall. This operation was described in the section under wave detectors. The rock involved was a massive limestone and did not exhibit any anisotropy.

Another special situation was an investigation to determine anisotropy effects on velocities and interfaces. Two locations were used, both on similar metavolcanic rock. The rock exhibits prominent cleavage in a direction N 20-30° W, with a dip of about 55-75° NE.

A rosette of six seismic lines was run at each location. The first line in each rosette was oriented due north, the second N 45° E, the third east-west, the fourth S 45° E, the fifth parallel to the cleavage and the sixth normal to the fifth. The lines were run with the Electro-tech using 20 foot geophone spacings and explosives as the wave source. Figure 12 shows a plan view of one of the rosettes.

All of the lines show a layer with a velocity of less than 2000 fps to a depth of from 6 to 8 feet. All of them also show a high velocity of from 13,000 to 14,000 fps, either directly beneath the surface layer or beneath an intermediate layer. The intermediate velocity of 4000 to 5000 fps is present on one or both ends of all the lines. The pattern is consistent, showing a weathered zone which thins out to the west of the rosette center.

In each rosette, no large variation in velocities was found to exist between any two lines at right angles to each other and any other two similarly opposed lines. A slightly greater depth to the second interface was indicated where the second interface was shown on both ends of the time-distance graph. This difference amounted to about 2-3 percent of the total depth to that interface.

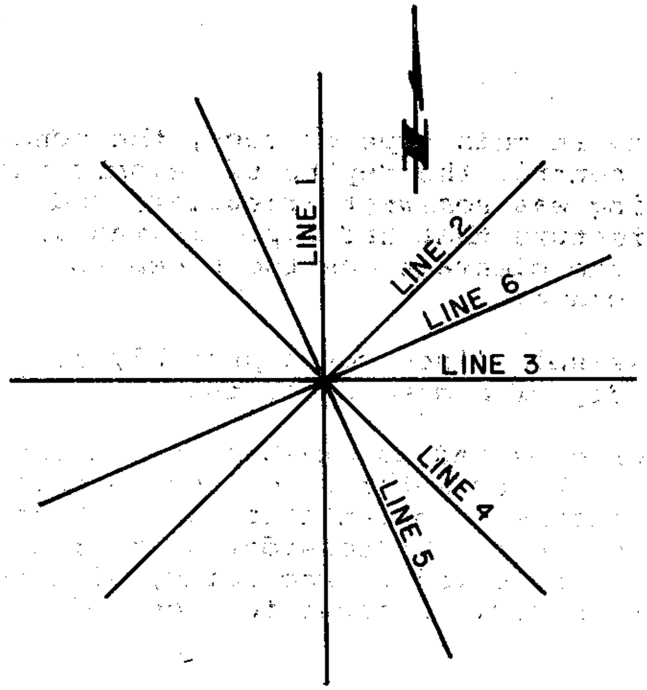


Fig 12 A plan view of the rosette of six seismic lines run in an attempt to detect anisotropy.

It was concluded that, in this type of rock, the zones of weathering appear to control the depths of seismic interfaces. The depth of weathering was somewhat irregular, and did not constitute a planar feature that had dip. It was also believed that the attitude of the cleavage was too steep to be represented on the time-distance graph.

This arrangement of seismic lines could probably be used for determining the true dip of bedded deposits.

This material had been expected to exhibit anisotropy with the velocity influenced by the orientation of the seismic lines. The variation of velocity with orientation was not significant enough or consistent enough to be considered the result of anisotropy. The errors involved in recording, picking times, and plotting the results could account for most of the variation.

SHEAR WAVES

It had been anticipated that major benefits could be derived from the use of shear wave velocities. Such things as anomously high compressional velocities, depths to water table, and dynamic moduli are examples of areas where these data were expected to be of value. It had been our understanding that the generation and recording of shear waves was a much simpler procedure than our experience has proved it to be.

The process of developing a satisfactory coupler for use in generating shear waves involved many different couplers over a period of approximately two years. During that time, some shear wave data was collected using different couplers at many different localities. At many of these locations, the direct wave was recorded but not the refracted wave.

A method did result from this study that was usually successful in generating and recording horizontally polarized shear waves (SH waves). The method used an aluminum coupler placed beneath a truck wheel as described in the section on shear wave sources. The field procedure used two geophones buried about 6-8 feet on each side of the seismic line and equidistant from the hammer station. The geophone signals were recorded using the Huntec instrument. This instrument was used because of its ability to correlate two separate, in-phase signals; and because of its internal gain control, which allowed it to display the complete waveform. Figure 13 shows the Huntec record for a shear wave line replotted on a time distance graph. Notice the parallel nature of the later arriving SH waves.

Two vertical geophones were planted near the horizontal geophones to receive compressional waves generated by vertical blows to the top of the aluminum bar. The compressional wave was recorded at each hammer station to be used as another means of determining the validity of the shear wave. By comparing the two wave trains, it was easy to determine whether an arrival was a later compressional event or a first arrival shear wave.

Figure 14 shows the complete waveform resulting from a vertical blow to the top of the aluminum bar. Notice the zone of interference in the first 40 feet of the record.

The difference in arrival time between the compressional and shear waves in the first few feet is quite small, and often results in only the P wave being displayed on the record for the first 40 to 100 feet. Beyond the zone of interference which cuts off the parallel rows of P wave arrivals is the vertically polarized shear wave (SV wave). It also exhibits parallel rows of later events until it is cut off by the surface wave arrivals. When the test area has a fairly uniform surface layer of several

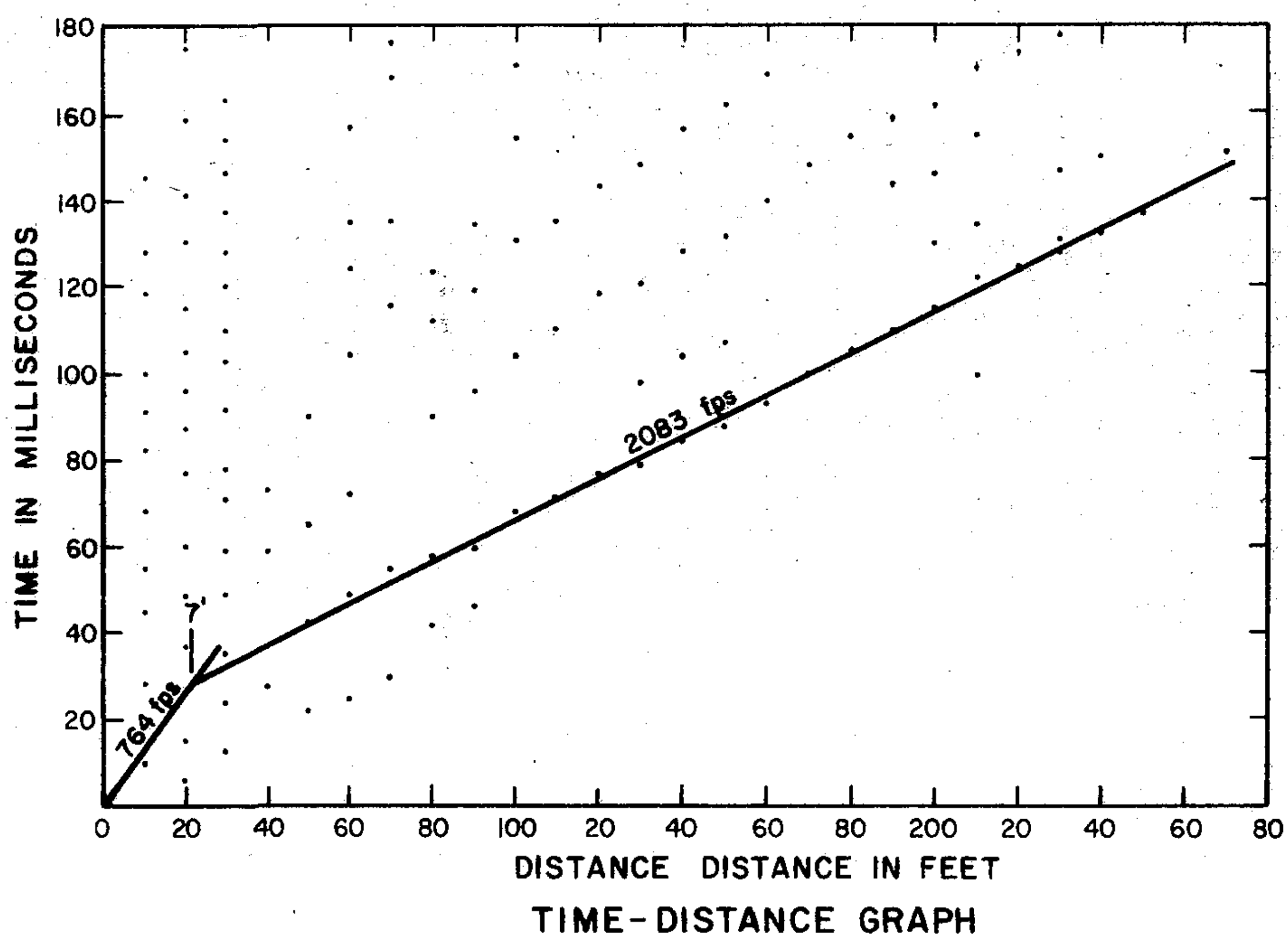


Fig 13 Time-distance graph showing the first arrival SH waves from horizontal hammer blows against the aluminum bar.

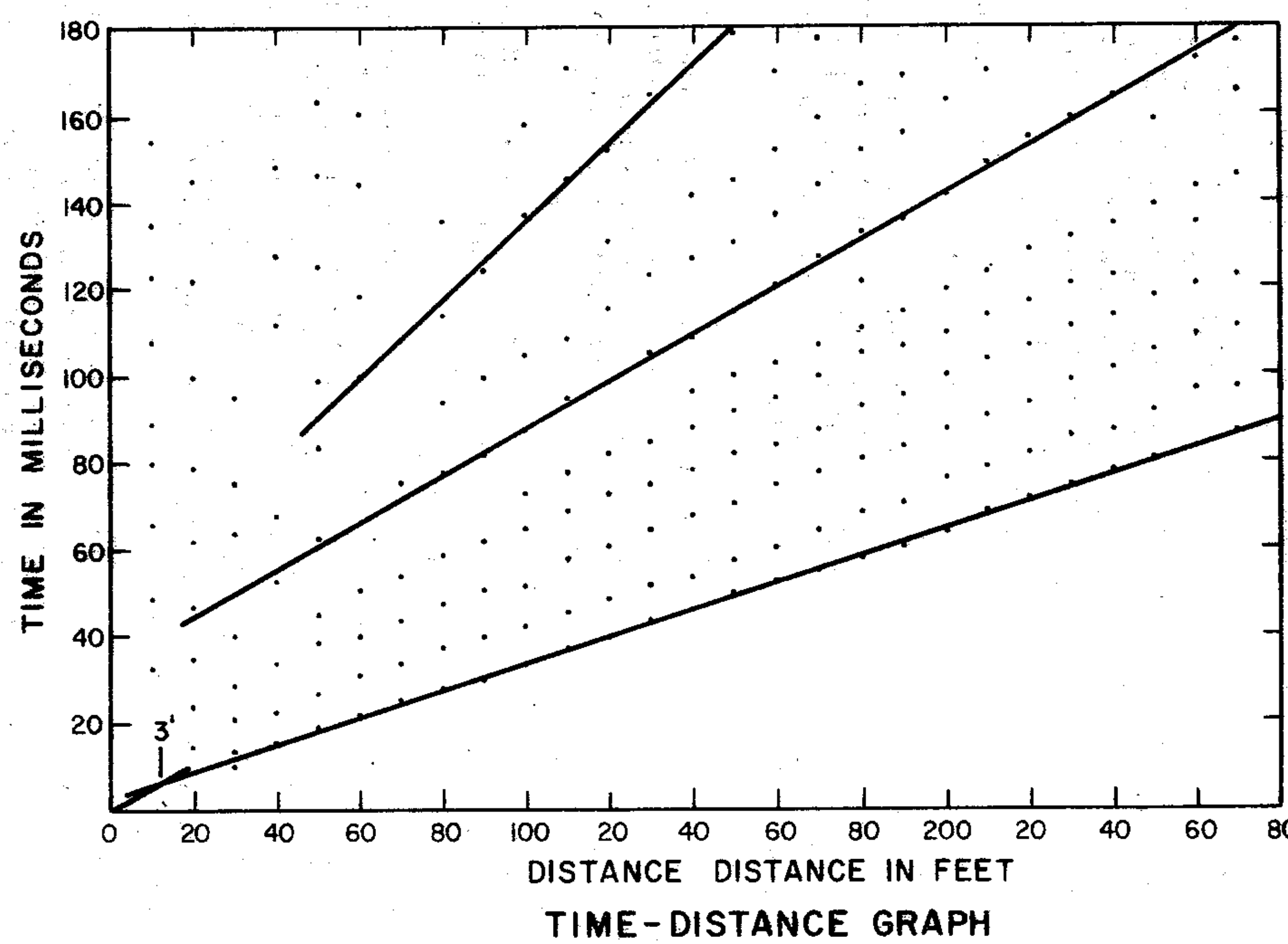


Fig 14 Time-distance graph showing arrival times of waves from vertical hammer blows, received by vertical geophones. Notice the clear alignment of SV and Rayleigh waves. Same location as Fig 13.

tens of feet thickness, the direct SV wave would be recorded as shown. The most dependable procedure for recording SV waves seemed to be one using arrays of vertical geophones and vertical hammer blows. This arrangement generated strong compressional waves as the first arrivals and could therefore only be used with an instrument using some form of internal gain control.

The amount of time that was spent in developing a method for generating and recording shear waves was greater than had been anticipated. As a result, very little shear wave data was obtained from problem areas where such data was expected to be of the most use. Also, because of the press of time, no data was available for predictions of subsurface conditions based on information from shear velocities.

A summary of the results at different locations where attempts were made to collect shear waves is as follows:

Little Sur River. The lines were run on loosely cemented sandstone. SH waves of fair quality were recorded with the Huntec and pendulum. The Electro-tech recorded only P waves using the same geophones and energy source. The horizontal geophones were very sensitive to wind noise.

Twin Bridges. The rock was massive hard quartz diorite. SH waves were recorded with the Huntec, using horizontal sledge hammer blows against the rock face. Only P waves were recorded with the Electro-tech using the sames phones and energy sources. The Electro-tech was operated at both half and full gain with no difference in the results.

Mountain Quarry. The rock was hard massive limestone. SH waves were recorded with the Huntec and horizontal geophones using an explosion in boreholes as the energy source.

Yolo Bypass. The material was soft to firm, sandy, clayey soil. Attempts were made to collect SH waves with all three instruments. The couplers used were the pendulum, the 1-1/2 inch by 4 foot bar, and the chair shaped plate. All three couplers tended to become loose under repeated impacts of the hammer and when loose, they generated more compressional than shear wave energy. The pendulum was the best of the three couplers tried. Good quality SH lines were recorded by the Electro-tech and the Huntec, but the Bison recorded only P waves.

Halloran Springs Rest Stop. The material was dry sandy alluvium. An attempt was made to collect SH waves with the Electro-tech using the pendulum and horizontal geophones. The amount of wind noise on the records made them unuseable. P waves were recorded at the same site a few minutes later using vertical geophones and vertical blows, without interference from wind noise.

Very good SH waves were obtained with the Huntec using horizontal geophones and horizontal blows against the aluminum plank.

Very good SV waves were obtained using the vertical geophones and vertical hammer blows to the top of the aluminum plank. The material at the site was essentially a single layer case and the SV signals came in very clearly. The method used for plotting the times of all arrivals made it very easy to distinguish each different wave form. See Figure 14.

Granite Bay. A thin granitic soil was overlying weathered granitic rock. The Huntec was used along with the aluminum bar as the coupler. The results were only fair to poor.

Sylmar. The material was dry sandy alluvium. The Huntec and the vertical array geophones were used to collect good SV waves from vertical blows. The same instrument was used with horizontal geophones and blows to obtain SH waves.

As the study progressed, the velocities were compiled along with other data necessary to calculate dynamic moduli. The data is shown in Figure 15 on a graph patterned after the work of Patterson and Meidav (15) with the dynamic modulus of elasticity as the abscissa and the compressional velocity as the ordinate. Additional data are needed to delineate the higher velocity portion of the curve. However, there appear to be a correlation between the compressional velocity of a material and the dynamic modulus of elasticity that can be interpreted from the graph on the basis of the compressional velocity alone.

The work of Erickson, Miller and Waters (6) and by Chang and Ballard (2), seems to indicate that a vibrator may be better than an impact for generating shear waves. At the present time, such equipment is quite expensive and is too heavy to be very portable. Additional study should be made to determine if this method could be adapted to routine field investigations.

$$E_d = \frac{(Vs^2)(\text{Lbs ft}^3)(2)(1+\sigma)}{(144)(g)}$$

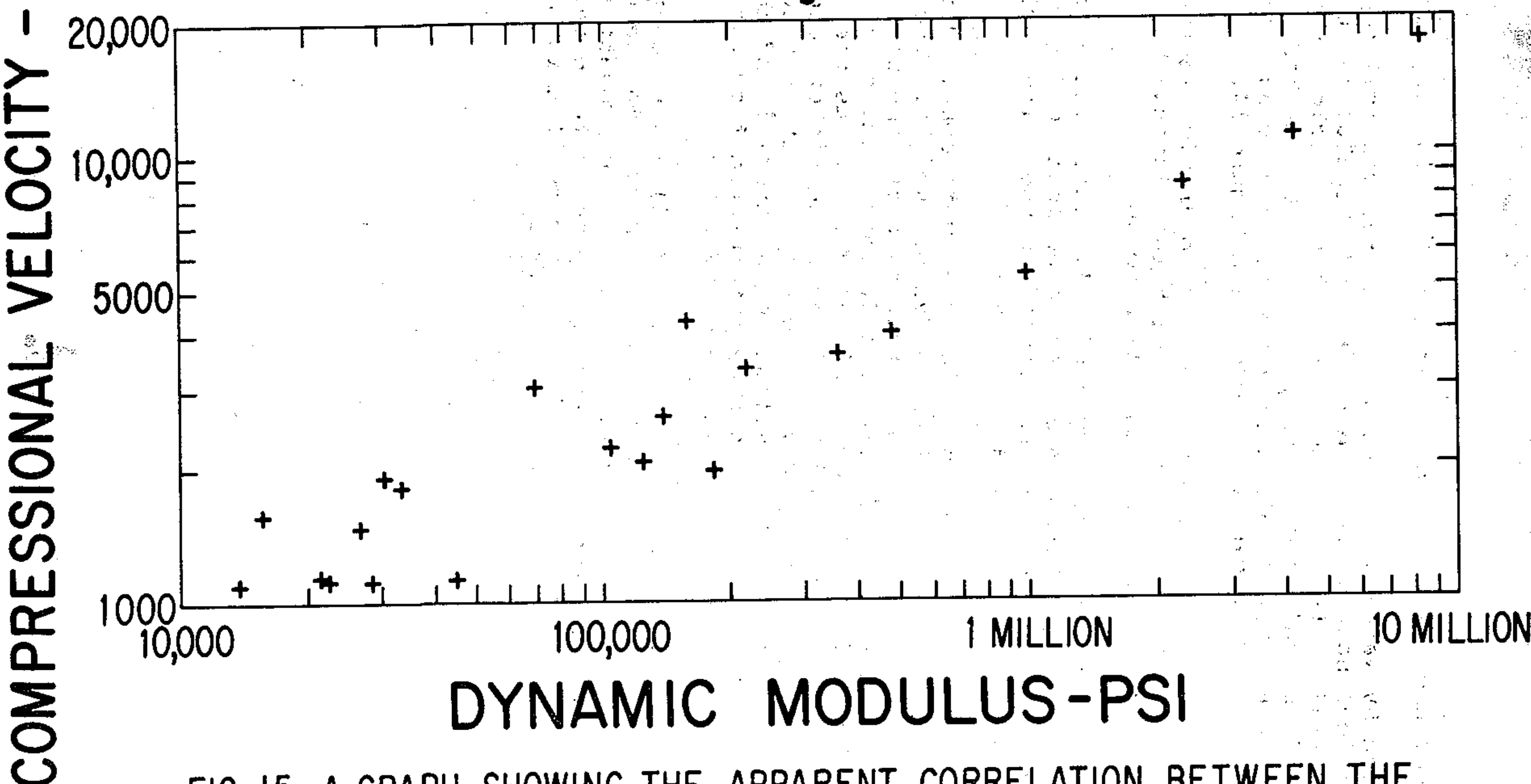


FIG. 15. A GRAPH SHOWING THE APPARENT CORRELATION BETWEEN THE DYNAMIC MODULUS AND THE COMPRESSIONAL VELOCITY

REFLECTION METHOD

The attempts to collect data from shallow reflections were based on the use of the correlator circuit in the Huntec instrument. This circuit enables the instrument to record in-phase arrivals and exclude out-of-phase arrivals.

Two methods of laying out the geophones and strike plate were used when trying to get reflections. One was a constant spacing profile and the other was an expanding spread.

The profiling method kept the distance between the strike plate and geophones constant. After a series of blows at any position, both the hammer and geophones were moved along the line a fixed distance as illustrated in Figure 16.

For the expanding spread method, the distance between the hammer and geophones was increased between each series of blows. Figure 17 illustrates this method. The distance between the hammer and geophones was measured to a point midway between the two arrays.

Both methods used two geophone arrays spaced a distance apart that was based on the apparent wave lengths of the refracted and reflected waves. The object was to record a wave picked up by both arrays at the same time, and to cancel a wave that arrived at the two arrays at different times. The geophone arrays were separated by the calculated distance along the seismic line with each array spread normal to the direction of the line. In theory, this would record reflected waves that arrived traveling in a near vertical direction and discriminate against refracted waves traveling in a near horizontal direction. A complete description of the method and the principles involved is to be found in the paper by Meidav (11).

Attempts were made to get reflections at seven different areas within the state. There were no reflections at four areas, doubtful results at two and apparently good reflections from one area.

The seven different areas tested represented widely different geologic and surface conditions. At two locations, the noise level was higher than the signal level and no records could be obtained. At one of the other locations the geology was unfavorable and no records could be obtained. At this site there were several layers of different material within 50 feet of the surface.

At Halloran Springs Rest Stop, the other location where no reflections were obtained, both the expanding spread and the profiling methods were used. The expanding spread was tried

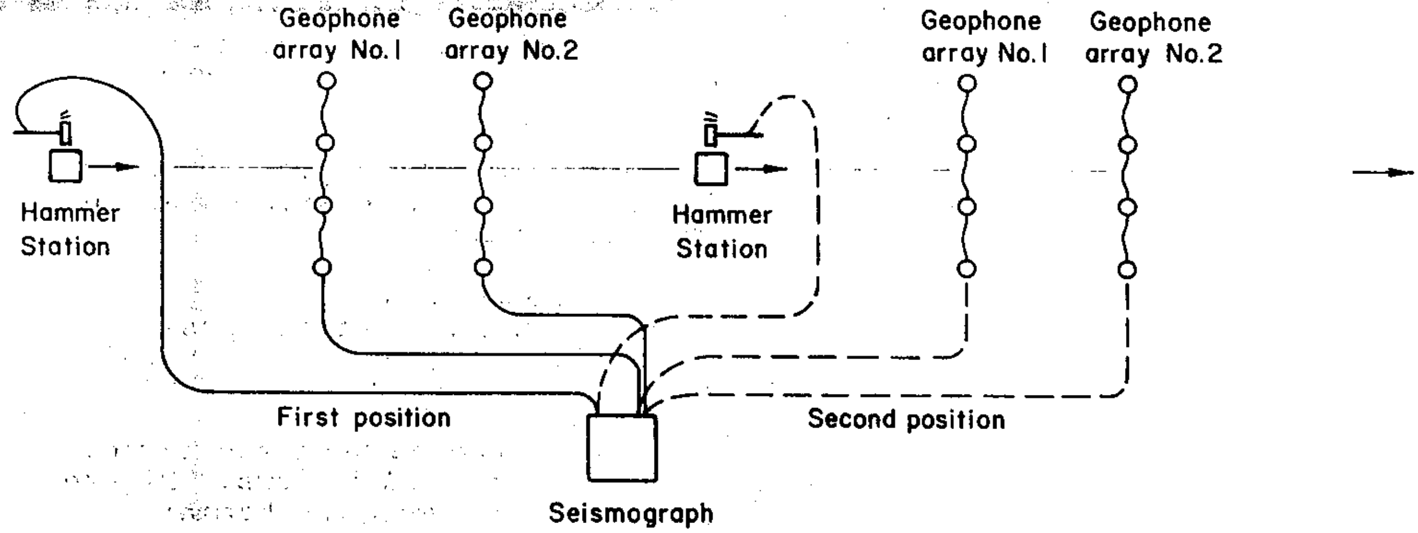


Fig 16 View showing the arrangement of hammer and geophones for the profile method of obtaining reflections from hammer blows. The hammer and geophones are moved an equal distance along the line from the first to the second position.

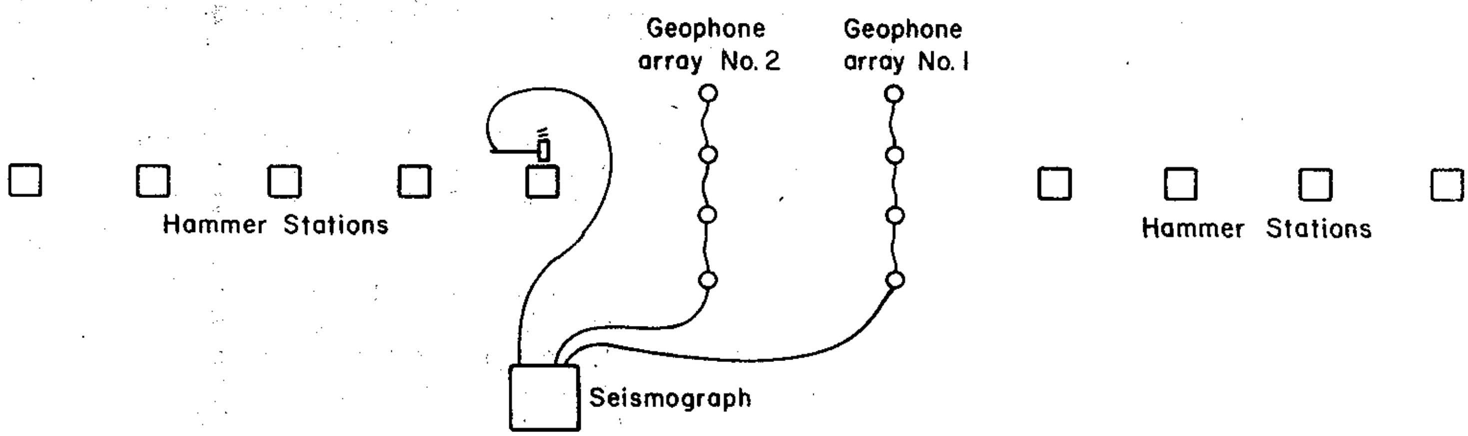


Fig 17 View showing arrangement of geophones and hammer stations for expanding spread method. Hammer stations are expanded both directions from center of geophone arrays.

many times over a period of several days. Most of the lines run during this period recorded refraction data, but there were no recognizable reflections.

The profiling method was then tried in the same area. One profile was near a large outcrop that, according to refraction data, extended under the alluvium at shallow depth. Another was beside a well that had been drilled through alluvium to a hard layer at a depth of over 100 feet. Other were run at locations corresponding to the location of the expanding spread attempts.

Neither of the known hard layers were located by this method. The data points on the record were mostly repeatable, but had the general appearance of random noise. If the times were reflections, they were being reflected from different levels in the alluvium, and so could not represent a single continuous layer. It is possible they represented interformational reflections from boulders, beds or local hard spots.

The material at the Hidden Hills location was very similar to that at Halloran Springs Rest Stop. However, there were more fines and no boulders. There was a boring at the site that was used to obtain uphole velocities. Refraction velocities were obtained at the location of the attempted reflection line.

A reflection profile was then attempted which gave a number of arrival times that might have been reflections. Since this method gives only total travel time, it is necessary to know either the depth or the velocity to determine the other. Using the uphole velocity and the recorded travel time gave a minimum depth to the reflector that was considerably deeper than available information. It was, therefore, impossible to determine the validity of the travel times.

At the location near Escondido, the material was a thin soil over weathered granitics with granitic rock at depth. Expanding spreads were run in conjunction with refraction and uphole surveys. The weathered granitic material is quite uniform and does not exhibit any anisotropy according to the surface refraction lines. The results from the uphole, refraction and reflection surveys are in agreement. Because the velocities as well as the depths agree, it is not possible to state conclusively that they are three different waves. It is possible the uphole and refraction velocities are identical. If this is so, the reflection times may actually have been late arriving refractions.

The reflecting layers at this site would have to be very shallow in relation to the length of the expanded spread. The path of a wave reflected from one of these layers would, therefore, be largely horizontal. Under these conditions, it might not be possible to determine whether a wave was refracted or reflected. The velocities obtained by each of these methods are shown in Tables 7 and 8.

Table 7

Subsurface Depths by Various Methods

Boring R88

Method	Depth Interval	Velocity or Material
Boring log	0-5 ft.	Soil
	5-50 ft.	Disintegrated granite
	50-90 ft.	Harder DG
	90-95 ft.	Hard DG
	95-110	Moderately hard DG
	110-140	Hard DG
	below 140	Fresh Rock
Seismic Refraction	0-5 ft.	1600 fps
	5-22 "	2600 fps
	22-80 "	3300 fps
	80-140"	4500 fps
	below 140	13000 fps
Seismic Reflection	0-57'	2600 fps
Seismic Uphole (TD graph solution)	0-45'	2250 fps
	45-105	3350 fps
	105-140	5000 fps

Table 8

Boring R86

Method	Depth Interval	Velocity or Material
Boring Log	0-5 ft 5-55" 55-95" 95-156	Soil DG Harder DG Rock
Seismic Refraction	0-5 ft 5-38 " 38-110 ft below 110	1500 fps 3000 fps 3650 " 13000
Seismic Reflection	50 ft	2800 fps
Seismic Uphole (TD graph solution)	0-52 ft 52-97	2300 fps 9200 fps

Seismic refraction, reflection and uphole velocities were obtained at the two borings. These, and the depths obtained by them are shown along with data from the boring logs.

The material at the location on Mare Island, where good reflections were obtained, was a wet soft clay overlying shale. The thickness of the clay was approximately 100 feet, which made the conditions nearly ideal for a hammer reflection survey. The type and thickness of material at this location had been determined by borings and refraction lines.

The first method tried was the expanding spread, using the Huntec instrument and array geophones. It was successful and reflections were obtained. The depths obtained by the reflection method were in excellent agreement with those from the refraction and borehole information as shown in Table 9.

An attempt was then made to use the Bison to get reflections, using the method described in their manual. This method was an attempt to enhance the reflected wave while cancelling the other wave arrivals. The hammer impact points were at distances of 50, 40, 30, 20 and 10 feet from the geophone. It appeared as though the reflection and another wave were arriving at nearly the same time. The repeated blows caused the two arrivals to move across the screen much like a ground swell. Repeating the operation with more than one blow at each hammer station caused the wave to appear like a larger ground swell. Consequently, it was not possible to identify reflections with this method.

The only location where reflections could be identified with certainty was at Mare Island. The thick layer of homogeneous material overlying the bedrock at this location is apparently necessary for the method to be successful. Such conditions are not usually encountered in engineering geologic investigations. The method is therefore quite limited in its usefulness.

TABLE 9

Subsurface depths and velocities at the Mare Island site.

Refraction Line	Depth	Velocity	Reflection Line		Borehole data
23		2500 fps	25	2550 fps to 100'	Soft peaty clay to 50'
	13'	3000 fps	26	2500 fps to 95'	Firm silty clay to 100'
	90'	9000 fps	27	2700 fps to 104'	
13		900 fps	28	1400 to 50'	Soft peaty clay to 50'
	10'	2000 fps		1900 to 79'	Firm silty clay to 70'
	50'	5000 fps	29	1650 to 50'	
			30	2250 to 76'	

UPHOLE VELOCITIES

Uphole velocities have been used in the past as a means of obtaining geologic information. They were usually obtained where it was not possible to get refraction data, either because of space limitations or because layers of low velocity underlay layers of higher velocity. They were also obtained in conjunction with refraction data when borings were available.

The uphole velocities have often been different than refraction velocities at the same location. They have also differed by being both higher and lower than the refraction velocities. Consequently, it has been difficult to correlate them with geologic properties. It was therefore decided to include them in this study to determine if they could be made more useful.

Uphole velocities were collected at three different locations. In addition, uphole velocities were used that had been obtained earlier at two other locations. Attempts were made to correlate these velocities with the physical properties of the material. An attempt was also made to correlate the uphole velocities with other seismic velocities obtained at each site.

The uphole travel times were obtained by geophones placed on the surface near the boring to be investigated. Explosives were detonated in the boring to provide a wave source. The first explosion was at the bottom, with subsequent shots placed at intervals up the hole. The normal interval was ten feet between shots.

The uphole velocities were calculated by two different methods. One method used a computer to calculate a velocity for each interval between shots. The program determined the shortest path between shot and geophone and the travel time used to follow that path. It then determined the distance traveled through the interval in question and the amount of travel time used for that distance, thus giving the velocity of the interval.

The other method used was a time-distance graph drawn using the uphole times and shot to geophone distance. The velocity was determined as being equal to the inverse of the slope of the line. Depths were determined by dropping a perpendicular to the ordinate.

A wave front diagram, using the method developed by Meisner (12), was also drawn for each boring where data was available. This method requires the geophone line to extend away from the boring like a refraction line. The travel time from any shot to each geophone is plotted beneath that geophone at the same depth as the depth of the shot. Contours were then drawn linking equal travel times. With this method of plotting, the wave is illustrated as having its origin at the top of the boring. The contours represent the wave front at any time. The velocity of the wave at any point can be determined by scaling the distance between wave fronts and dividing by the time interval.

At the Hidden Hills location the material was fine to medium grained alluvium. Uphole and refraction velocities were obtained. There was very good agreement between the depths and velocities from the refraction method and the uphole depths and velocities by the time distance graph method. The uphole velocities from the interval method were in fair agreement with the refraction data. There was no data available on the boring.

The material at the location near Escondido was weathered granitics overlying granitic rock. Two boreholes were drilled and logged at this site. Seismic data was obtained from refraction, reflection and uphole surveys. A comparison of all the data is shown in Tables 7 and 8. Both the uphole and the reflection data were from too shallow a depth to record the hard rock encountered in both borings. There was generally good correlation between the different data.

The boring logs give more interfaces than the refraction survey, but the refraction depths and velocities appear to be the important ones. The uphole velocities and depths from the time distance graph are in very good agreement with the refraction velocities. The reflection depths vary depending on which reflection line is considered, but they are mostly within 10% of the depths from the boring log or from the uphole survey. The reflection velocities are similar to the uphole velocities, but appear to be more of an average of the refraction velocities to that depth.

The uphole velocities obtained by the interval method do not correlate with the other velocities.

Wave front diagrams were drawn of the travel times from each of the two borings. Both of these diagrams show the material as being quite uniform. The wave front diagram at R-88 shown in Figure 18 shows a higher velocity area in the lower portion that is farthest from the boring. This may be a peculiarity of this method of illustrating arrival times. However, refraction lines near these areas seem to substantiate the higher velocities found here.

The wave front diagram at R-86, Figure 19, shows a higher velocity material in the lower portion which is closer to the boring. It also seems to agree with velocities from the refraction method. Good evidence of a fault crossing this area was found on three different refraction lines. The evidence of the fault also seems to be shown on this wave front diagram.

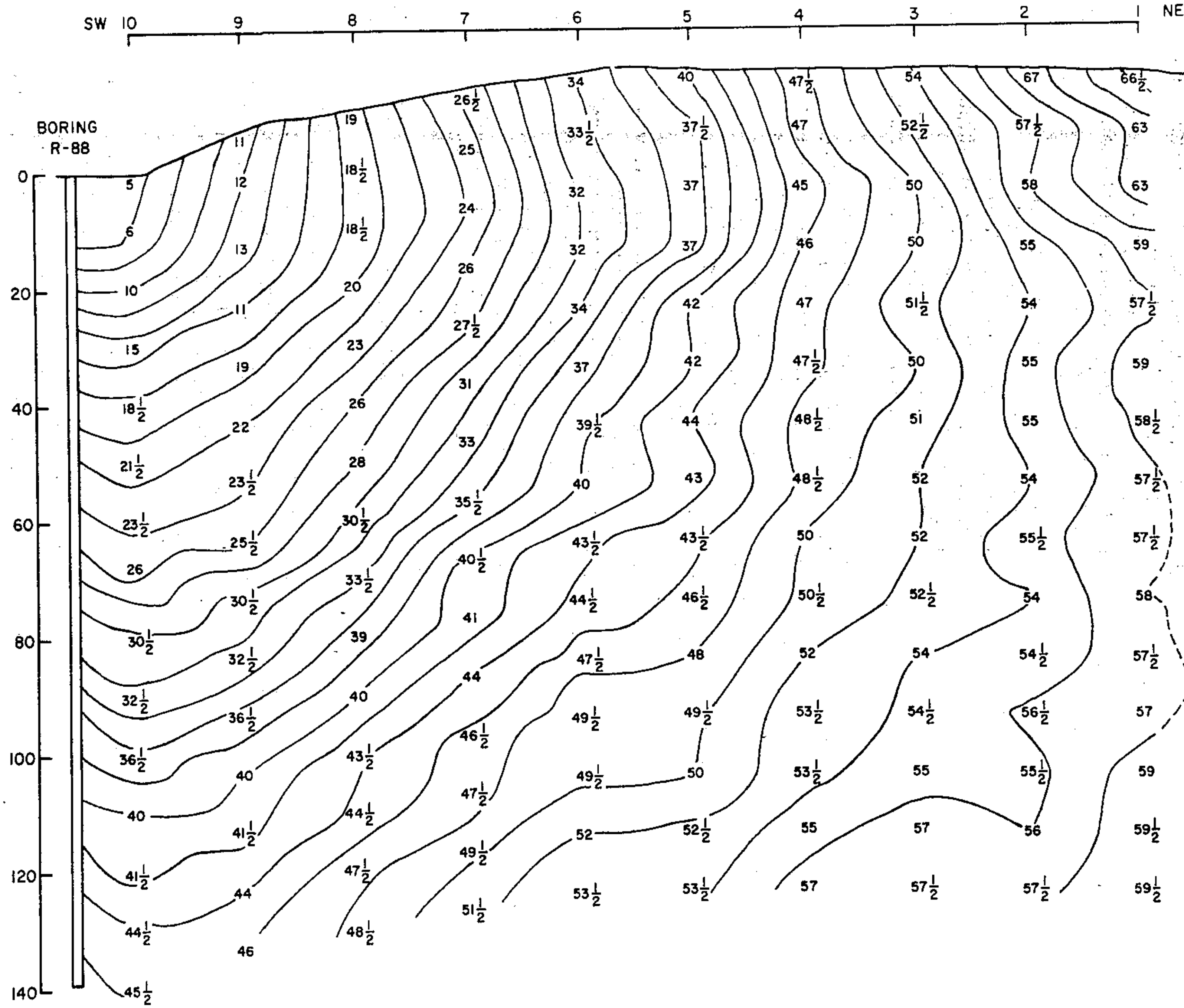


Fig. 18. Wave front diagram at boring R-88. Geophones 1 through 10 are located on the ground surface at the horizontal locations shown.

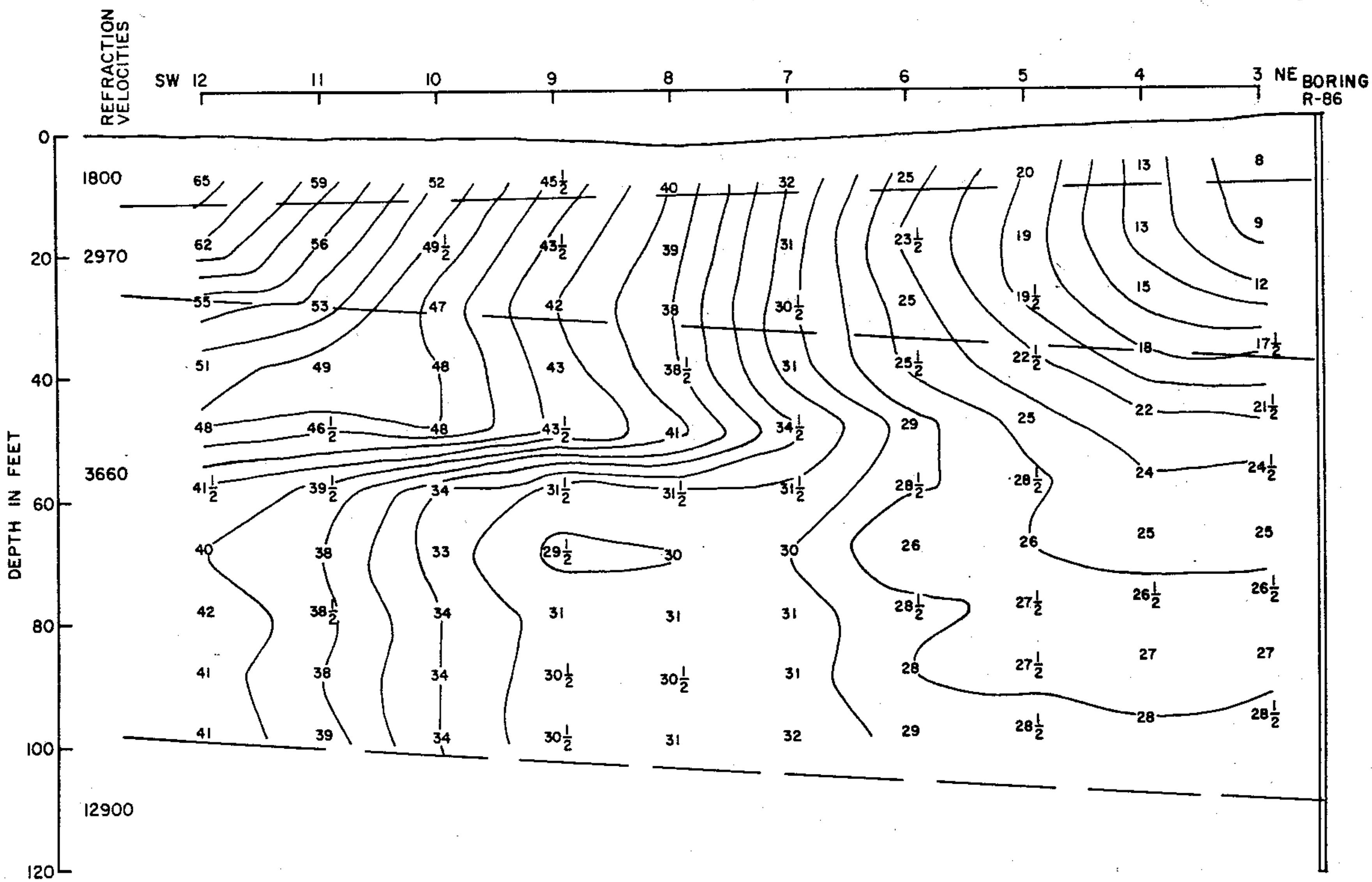


Fig. 19. Wave front diagram at boring R-86. Geophones 3 through 12 are located on the ground surface at the horizontal locations shown.
Dashed lines indicate refraction interfaces.

Uphole and refraction velocities were obtained at the boring site in the Kramer Hills. Neither of the two uphole velocities agree with those obtained by the refraction method. The wave front diagram was, of course, drawn from the same data as that used to calculate the refraction velocities. As a consequence of using the same data, the wavefront diagram gives a good graphical depiction of the refraction depths and velocities.

At Santa Susana Pass a large number of borings were made and used to obtain uphole velocities. Refraction velocities were also obtained wherever the topography allowed. The material was interbedded sandstone and shale and it was expected that softer material would underlie harder layers at some of the locations. There was only fair agreement between the uphole velocities and the refraction velocities obtained at the same locations. The uphole velocities by the interval method were inconsistent and did not seem to correlate with any of the other data. A prediction of the rippability of the material was made, based on the uphole velocities by the time-distance graph method. The correlation between the predictions and the actual method used during construction was only fair. In most cut areas, more blasting was predicted than was required during construction. However, in one cut area, the prediction was for less blasting than was required during construction.

The next site was shale and volcanic rock near Pomona. Both uphole and refraction velocities were obtained.

The uphole velocities by the interval method did not correlate with the refraction data or with the uphole velocities by the time distance graph method.

There was good corelation between most of the uphole velocities from the time distance graphs and the refraction velocities. They disagreed when the uphole showed alternating hard and soft zones. In view of the rock type, and since the refraction method cannot show soft layers beneath harder ones, this did not appear unreasonable at the time. Predictions were then made of the expected excavation characteristics based on each of the velocities. The predictions based on the uphole velocities by the time distance graph method, gave good correlation with the method used during construction, but were not as accurate as the predictions based on the refraction velocities alone.

There was no consistent relationship between uphole velocities and refraction velocities. The reason is not known, but two possibilities are suggested. One is that, in at least some cases, the vertical and horizontal velocities are not the same. The other is that the methods used to measure the travel times are too different in their degree of accuracy.

The uphole velocities calculated by the interval method are particularly susceptible to any error in the recording and measuring of the travel times. The difference in travel time between two adjacent shots is usually very small, often smaller than the resolving ability of the seismic timer. The travel distance is also small, so that small differences in time result in large differences in velocity.

Not enough reflection data was obtained to determine if there was a relationship between uphole velocities and reflection velocities. However, one of the conclusions of this study was that the hammer reflection method could only be used under the proper conditions of local geology. Therefore, it is probably too limited geographically to be of real value as a replacement for the uphole method.

The information provided by the uphole velocities did not correlate with the excavation characteristics as well as that provided by refraction velocities. In view of this, it is recommended that uphole velocities not be used for predictions of excavation characteristics or for the design of cut slopes.

An alternative method which could be used in areas where there isn't enough space for refraction lines, would be cross-hole velocities. This method would measure longer travel times, horizontally traveling waves and would be able to show low velocity layers below higher velocity material. This method would simply call for two borings, separated by a short distance. The geophone would be placed in one and the shot at the same elevation in the other.

SURFACE WAVES

The surface wave portion of this study was limited to a literature search. The object of the search was to determine if surface waves were something we should be measuring, and if so, how it was to be done.

The surface waves considered of interest were the Rayleigh waves. These are actually a combination of compressional and shear waves, with oscillations normal to the surface along which they are traveling, and parallel to the direction of propogation. This is the wave usualy seen on a record as ground roll.

The Rayleigh wave velocities are normally obtained using a vibrator as the wave source. According to the literature (1), (2), these velocities are then treated as shear wave velocities. The reasoning is that the Rayleigh wave velocity is 0.92 that of the shear wave, which in the range of velocities considered, is not significantly different. Heiland (9) shows Rayleigh wave velocities which are only 0.8 of the shear wave velocity in the same material. Incomplete results of our own work indicate that in some cases, the ratio may be as low as 0.7.

It is known that Rayleigh waves are dispersive; that is, the velocity varies with the frequency. When the frequency is high enough that the wave lengths are short in relation to the thickness of the surface layer, the waves will not penetrate the lower layer, and the velocity will be determined by the shear velocity of the surface layer. When the frequency is low enough that the wave lengths are long in relation to the thickness of the surface layer, they will penetrate the lower layer, and the velocity will be affected by the shear velocity of the lower layer. As a result, the Rayleigh wave velocity may be a function of the shear velocity of the surface layer, the underlying layer, or a combination of the two.

If the Rayleigh wave velocity is always 0.92 of the shear wave velocity, the examples of 0.8 and 0.7 are probably cases where the two velocities were not both measured in the same layer. Advance knolwedge of the condition of the material where the measurements are to be made would then be necessary to record the correct velocities.

Our present equipment is not adequate to use this technique for measuring Rayleigh wave velocities. It appears to be a way of obtaining information about dynamic properties that is not readily available by other means. It is therefore recommended that a vibrator type wave source be considered, along with the necessary equipment for recording the waves.

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GLOSSARY

ANFO - Ammonium nitrate and fuel oil, a non cap sensitive mixture that can be exploded with a cap and primer. Propagates at approximately 13800 fps.

Coupler - A device used to transfer the engergy from a hammer blow into the soil.

Shaped Charge - An explosive charge constructed in such a way as to direct the force of the explosion.

SH Wave - A horizontally polarized shear or transverse wave. The particle motion is horizontal and normal to the direction of travel.

Surface Waves - Seismic waves that travel along the earth's surface. Includes both Love waves and Rayleigh waves.

SV Wave - A vertically polarized shear or transverse wave. The particle motion is vertical and normal to the direction of travel.

Uphole Velocity - The seismic velocity obtained by detonating a charge at the bottom of a boring and recording the arrival time at the surface.